Introduction to Radio Science

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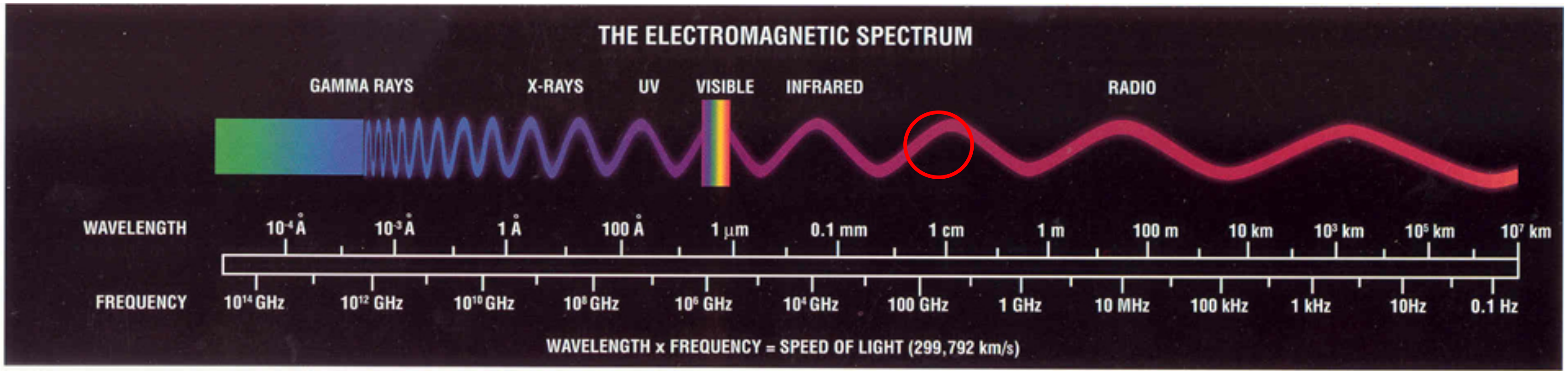
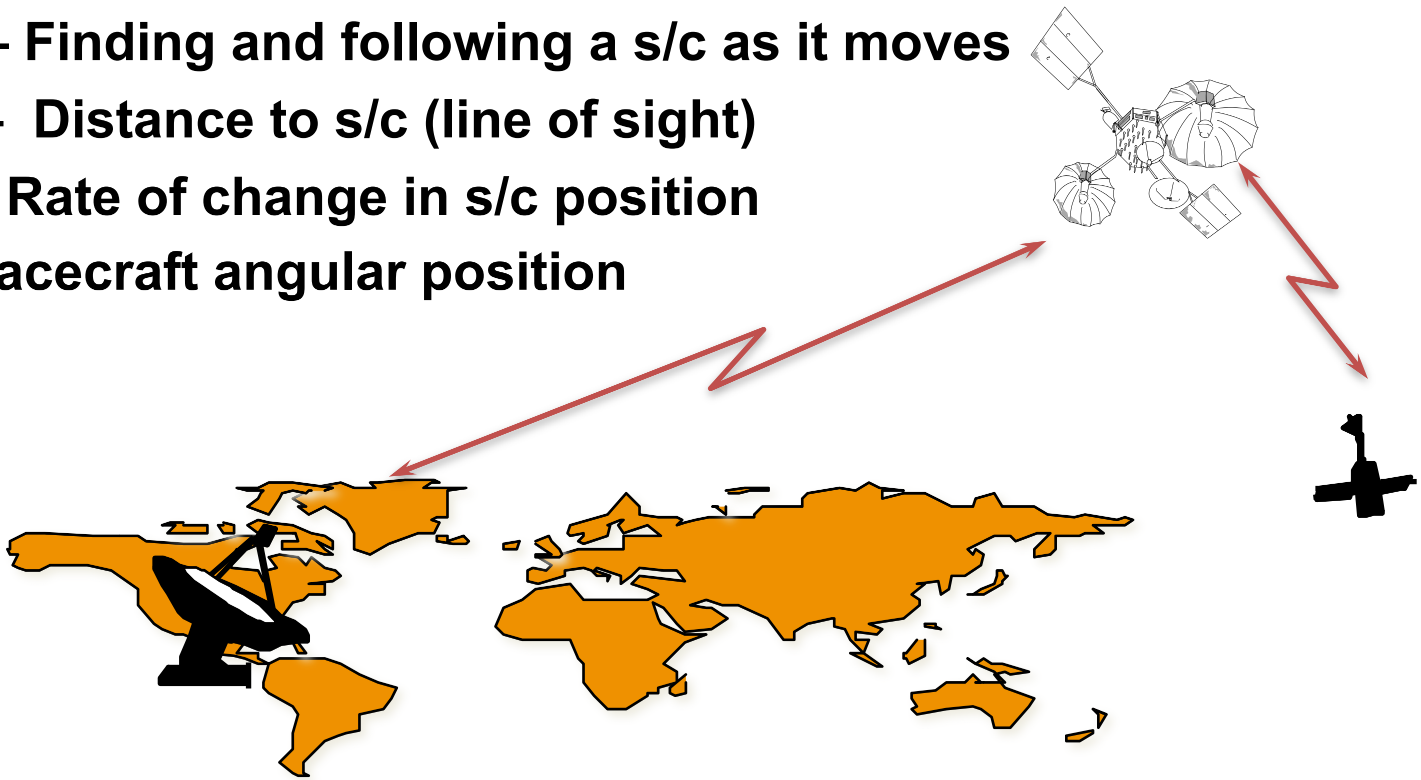
Radio Signals: Cell Phones to Deep Space

- International Telecommunications Union is UN treaty organization charged with *maintaining law and order in the use of the electromagnetic spectrum*
- Communications bands categorized by Near Earth & Deep Space
  – Propagation effects (effect of intervening media)
  – Communications performance (number of bits)
  – Evolving technologies (miniaturizing, power consumption)
- Three bands currently used by Deep Space network (S, X, & Ka)
  – S-band uplink in increasing conflict with cell phone usage
  – UHF from probe proximity links



Spacecraft Tracking Data

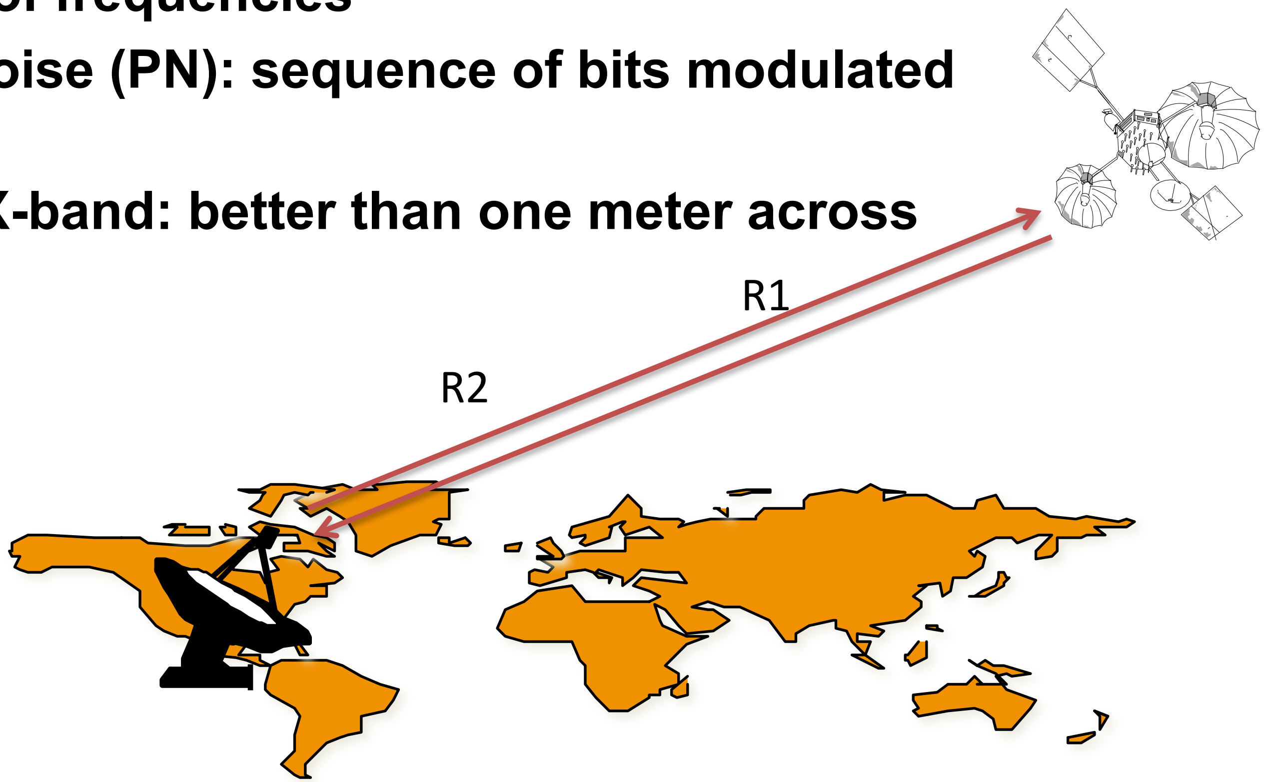
- Provide spacecraft position and velocity
  - Navigators solve current and predicts future state vector
- Tracking – Finding and following a s/c as it moves
- Ranging – Distance to s/c (line of sight)
- Doppler – Rate of change in s/c position
- VLBI – Spacecraft angular position



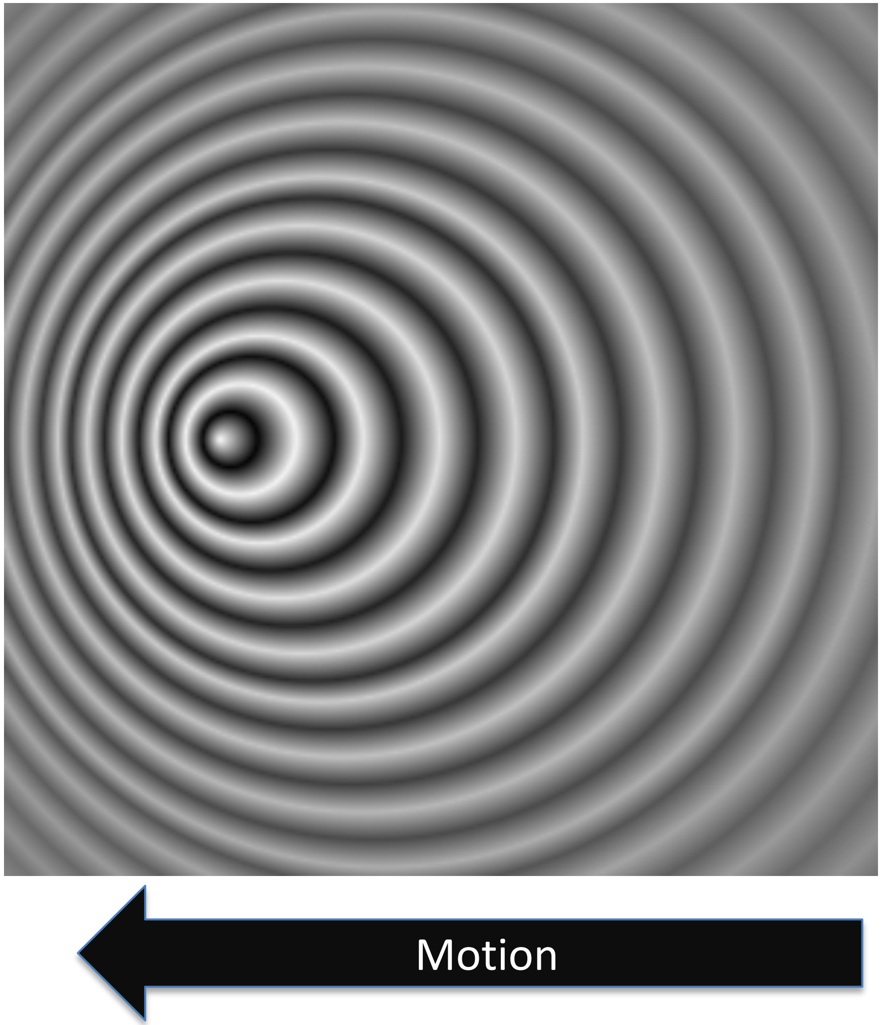
Radio-metric Data: Measurements using the radio signal and its variations.

Ranging

- Range is the distance between ground station and spacecraft
  - Measured as round-trip light time (RTLT)
  - Distance = (RTLT/2) * light speed
- Methods
  - Tone: set of frequencies
  - Pseudo Noise (PN): sequence of bits modulated on signal
- Accuracy at X-band: better than one meter across solar system



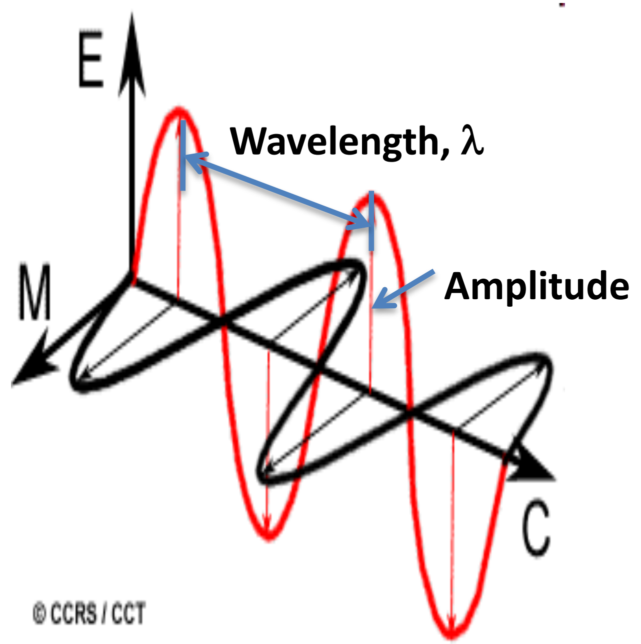
Doppler Effect



- An observed/perceived change in the frequency of a radio wave due to the relative velocity between transmitter and receiver
- Doppler is range rate
- The Doppler Effect changes the observed frequency for wave sources in motion
  - Approaching sources appear to transmit higher frequencies – blue shift
  - Receding sources appear to transmit lower frequencies – red shift
- Measuring the radio frequency from spacecraft allows us to determine the relative line-of-sight velocity between spacecraft and tracking station

Waves

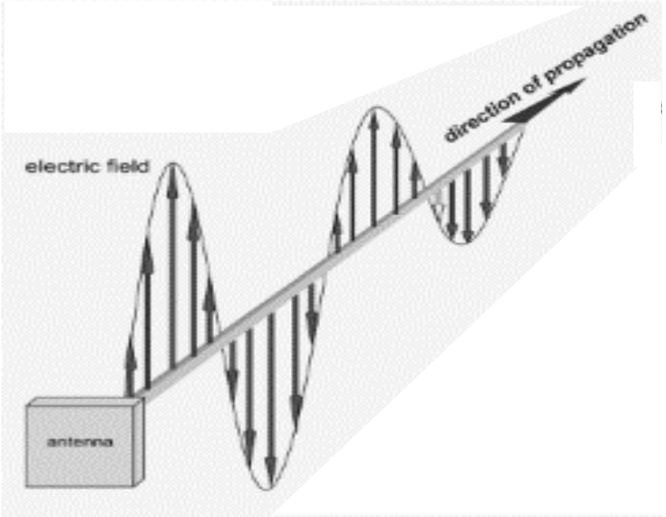
- Wave: energy moving through a medium
- Water waves: energy moves through water
  - Place a small piece of paper in a tub of water at one end. Make a wave at the other end. Note the wave propagates through the water, but the paper will bob up and down
- Sound: energy moves through air and matter
- Earthquakes: seismic energy moves through matter
- Electromagnetic: energy moves through a vacuum and some matter



Electromagnetic Wave Polarization

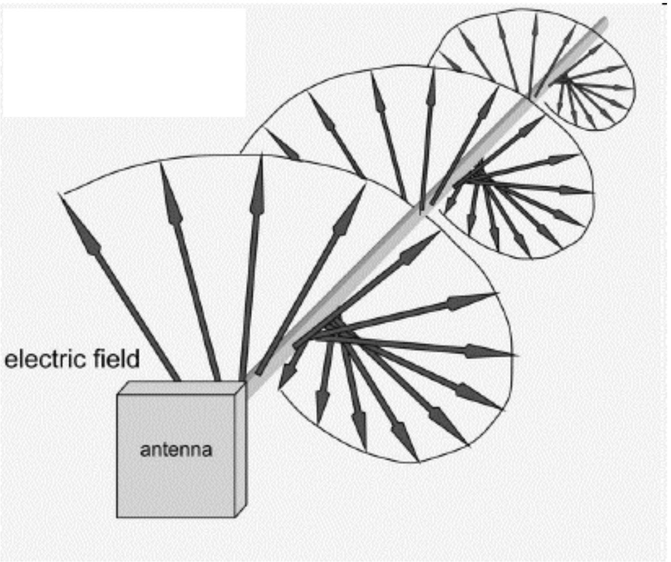
The polarization of a wave is determined by the orientation of the signal's Electrical field relative to the propagation vector of the wave

Selection for a specific satellite antenna is based on mission design requirements

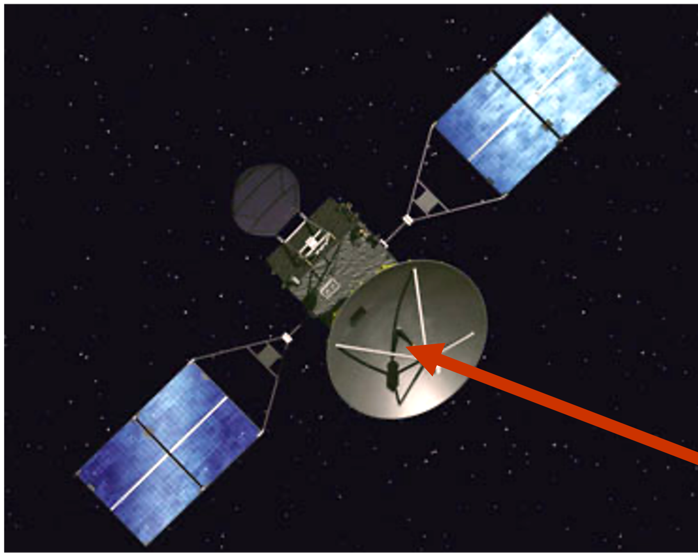


When the electric field oscillates in a plane perpendicular to the propagation vector, the signal is said to be <u>linearly polarized</u>.

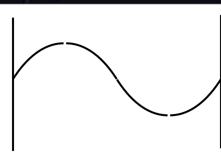
When the electric field oscillates around the propagation vector (oscillating through both planes in a corkscrew effect), the signal is <u>circularly polarized</u>.

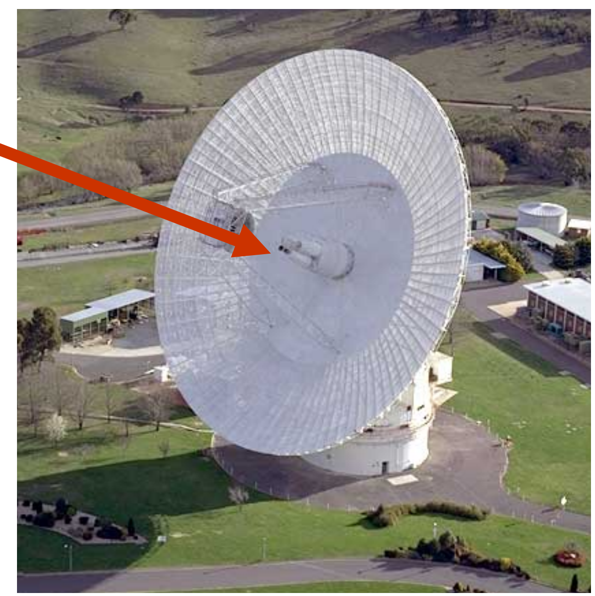


EM Wave Communication



Spacecraft communications are carried on electromagnetic waves that travel between ground facilities and satellites in space. These electromagnetic waves travel at the speed of light (3×10^8 m/s through free space).

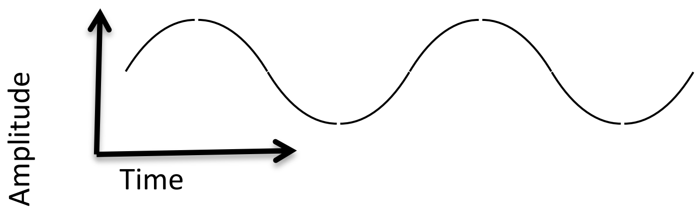


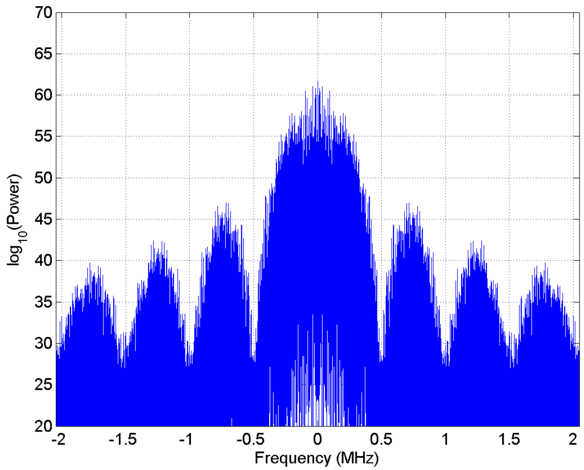


Electromagnetic waves used for spacecraft communication are generally cm or mm in length. The wave shown here is 3.6 cm in length – the wavelength of a 8.4 GHz signal.

Signals in Time & Frequency

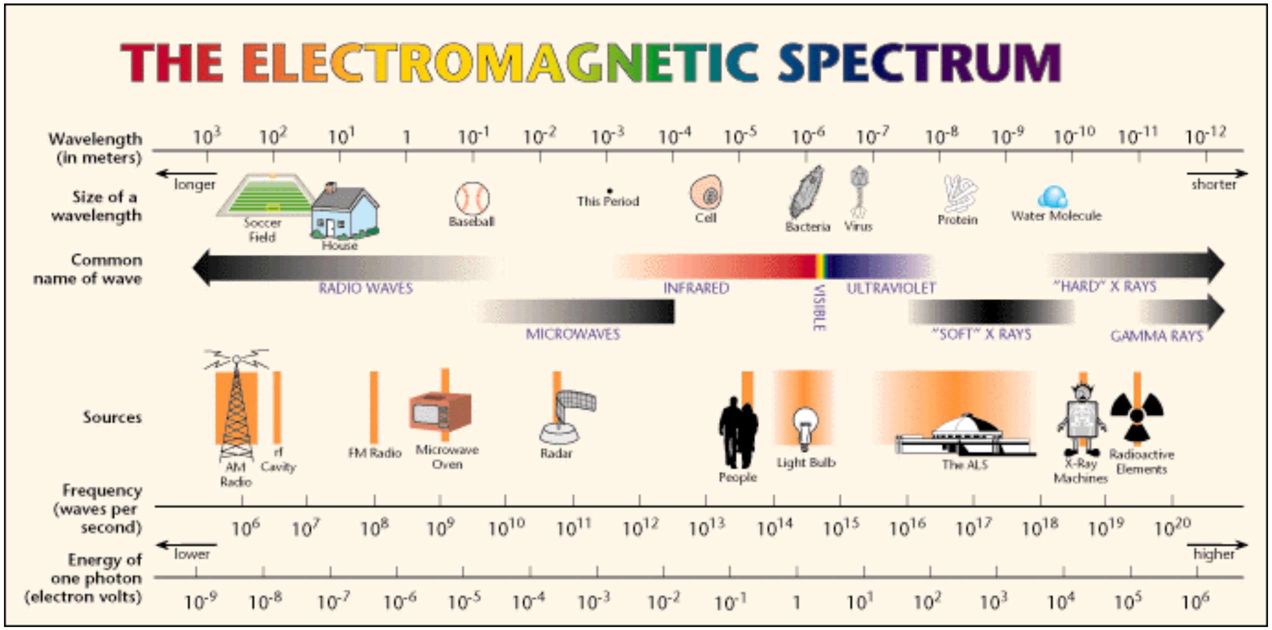
- Electrical communications signals consist of time varying voltage described in the time domain
- A signal's frequency domain description is its spectrum
- Spectral concepts describe a signal by its average power or energy content at various frequencies
- Spectra illustrate how much of the electromagnetic bandwidth the signal occupies





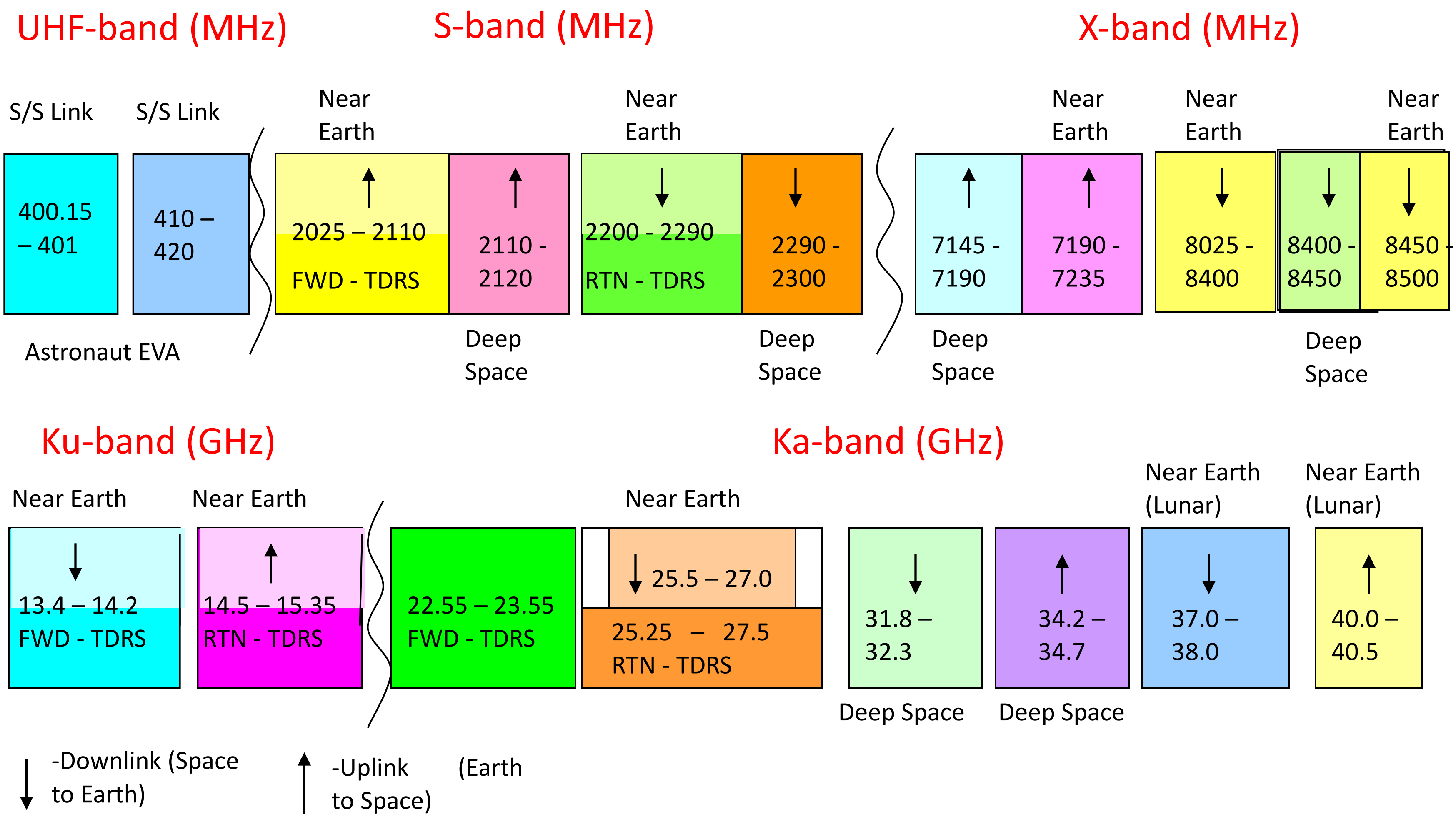
Interaction Between Waves & Media

- **Space allows electromagnetic waves to travel through it**
- **Earth's atmosphere has different effects on different wavelengths**
- **Frequency band chosen for communication through the atmosphere**

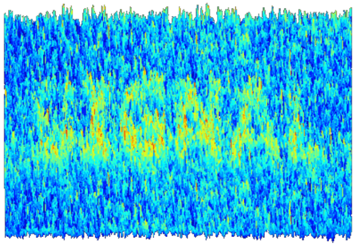


1) Microwaves pierce through fog and rain (greater signal loss at higher frequencies).
2) Microwaves from nature are very weak and do not cause much interference.
3) Microwave signals are easy to generate and to detect.

Commonly Used Communication Bands

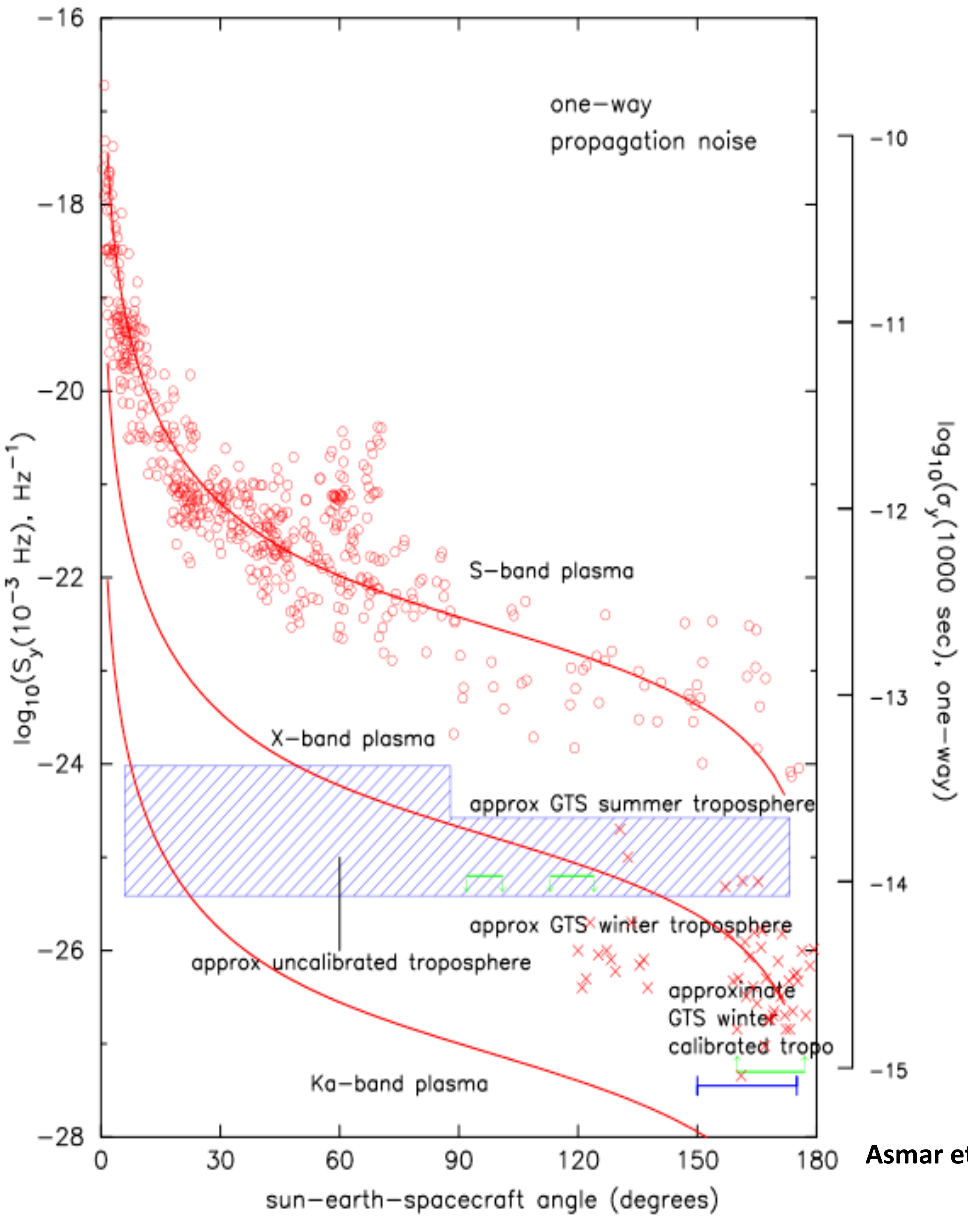


Noise



- Noise is additional "signal" not corresponding to information
- Introduces changes in ideal free-space signal; may lead to incorrect interpretation of information at the received signal destination
  - Signal noise
    - Amplitude noise – error in the magnitude of a signal
    - Phase noise – error in the frequency / phase modulation
  - System Noise
    - Component passive noise (heat)
    - Component active noise (amplifiers, mixers, etc…)
  - Environmental Noise
    - Atmospheric ionospheric or precipitation
    - Solar or Galactic
- Radio Frequency Interference (RFI) sources on Earth

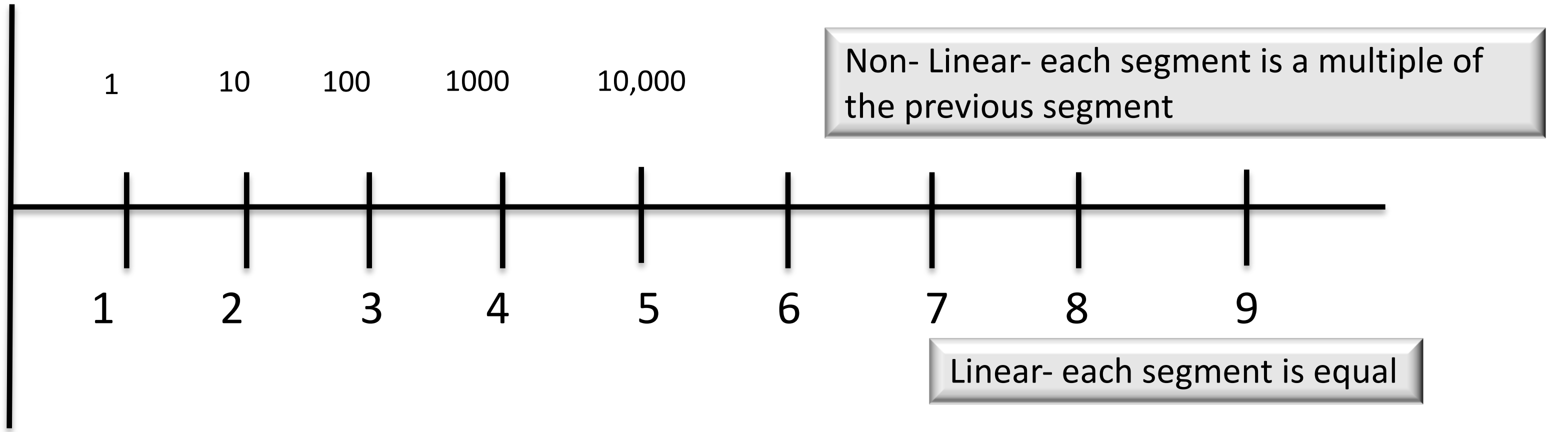
Dispersive Noise



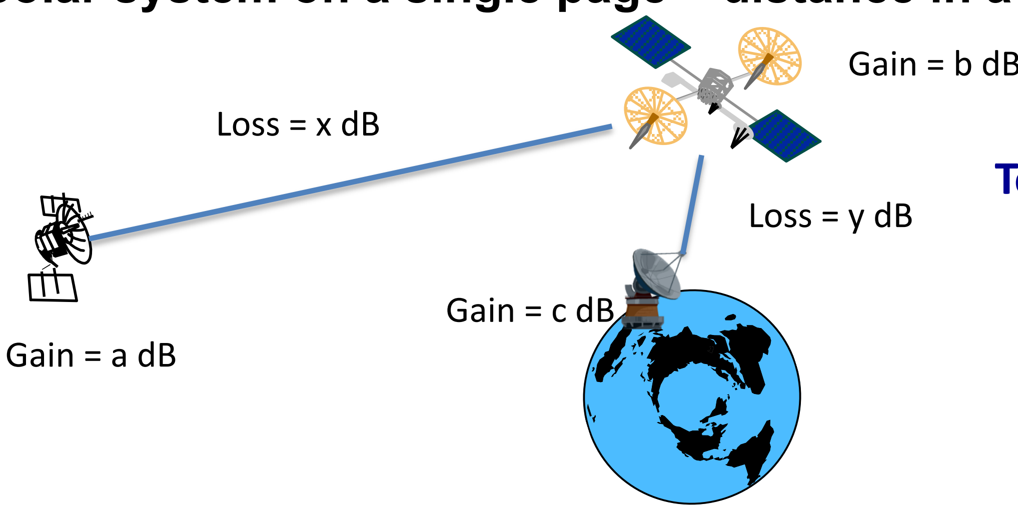
Asmar et al., 2005

- Contribution to noise from instrumental and natural sources have been examined by scientists and system engineers
- Noise in one-way propagation at S-, X-, and Ka-bands as function of angular distance from Sun
  - Also shows troposphere

Linear and Non-Linear Scales



- **Compare items with large values in comparison with each other**
  - **Hearing – measured in dB's**
  - **Earthquakes – measured on the Richter magnitude**
  - **Solar system on a single page – distance in a power ratio**



Total Gain = a + b + c – x - y dB
Can now simply add dBs

deciBels (dB)

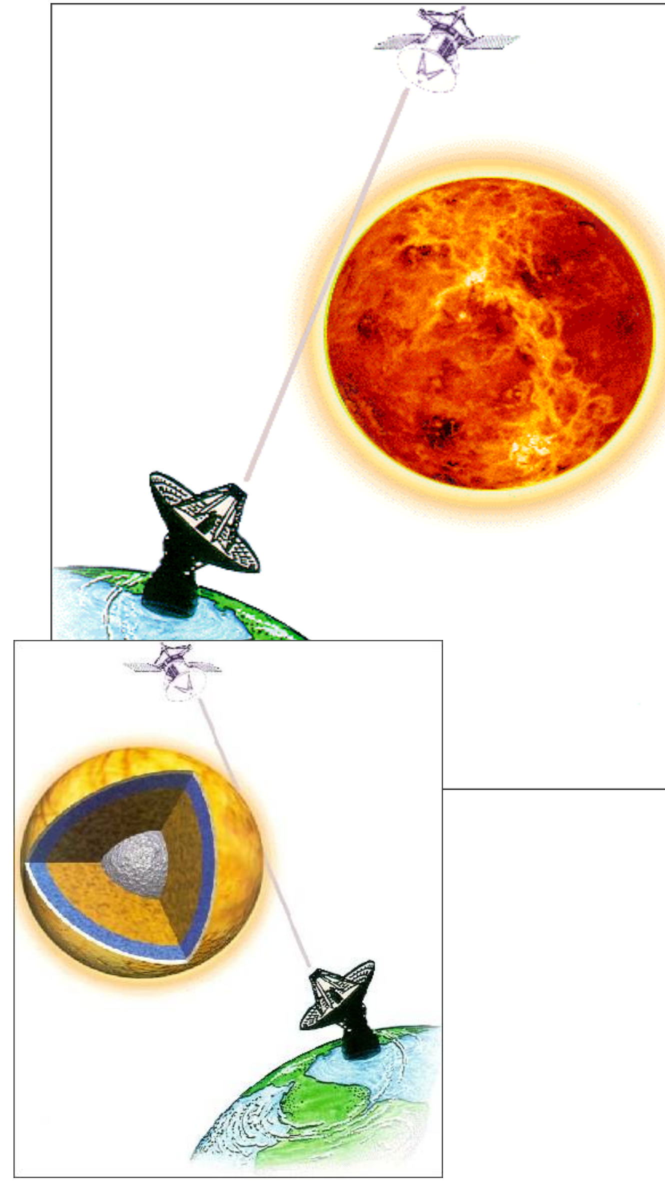
RF Signal Strength, RF gains and losses are typically expressed in a unit referred to as a decibel (dB).

- **Decibel = One-Tenth of a Bel**
- **A Bel is the logarithm (base 10) of the ratio between two values (e.g., power, current, voltage).**
- **Operation is addition instead of multiplication.**
- **To compute decibels using a power ratio, the basic formula is:**
  - **Decibels (dB) = 10 x $\log_{10}(P2/P1)$**

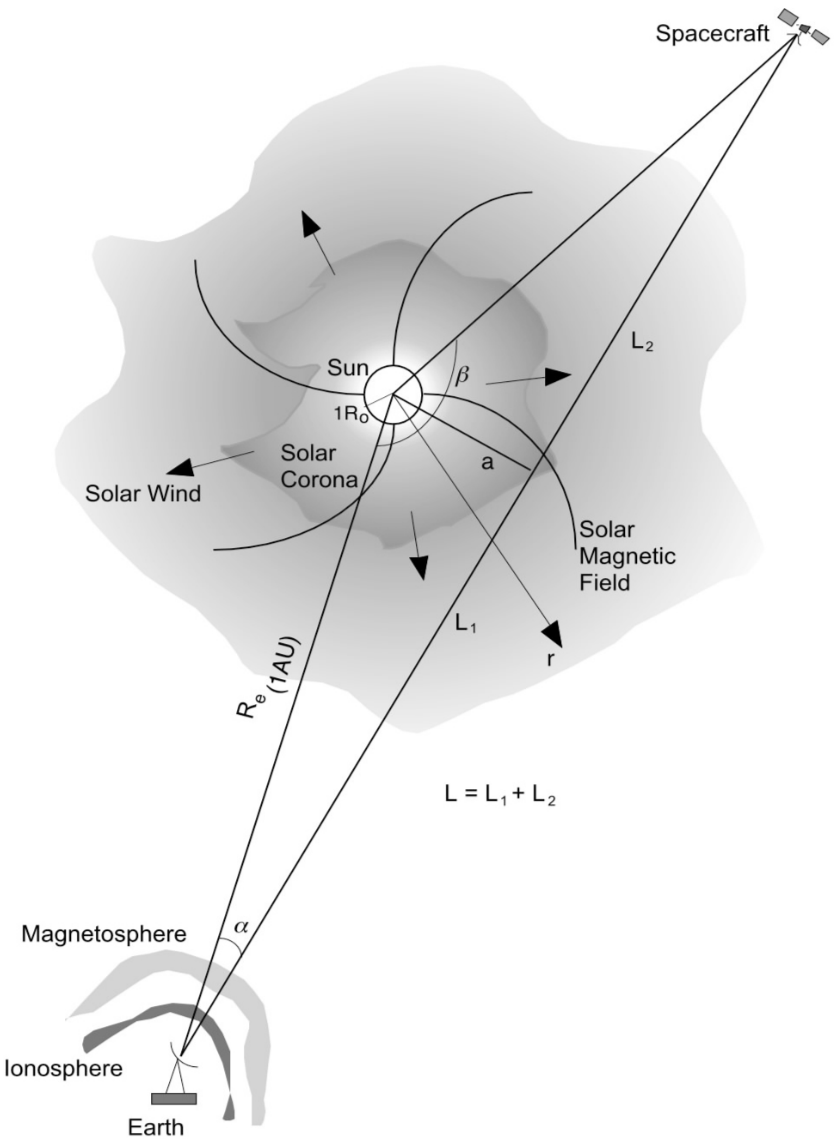
- Quick Refresher on Logarithms
  - The $\log_{10}$ of a number is the exponent that indicates the power to which the number 10 is raised to produce a given number.
  - So:
    - $\text{Log}_{10}(2) = 0.3$
    - $\text{Log}_{10}(4) = 0.6$
    - $\text{Log}_{10}(8) = 0.9$
    - $\text{Log}_{10}(10) = 1$
    - $\text{Log}_{10}(100) = 2$
    - $\text{Log}_{10}(1{,}000) = 3$

The Start of Radio Science

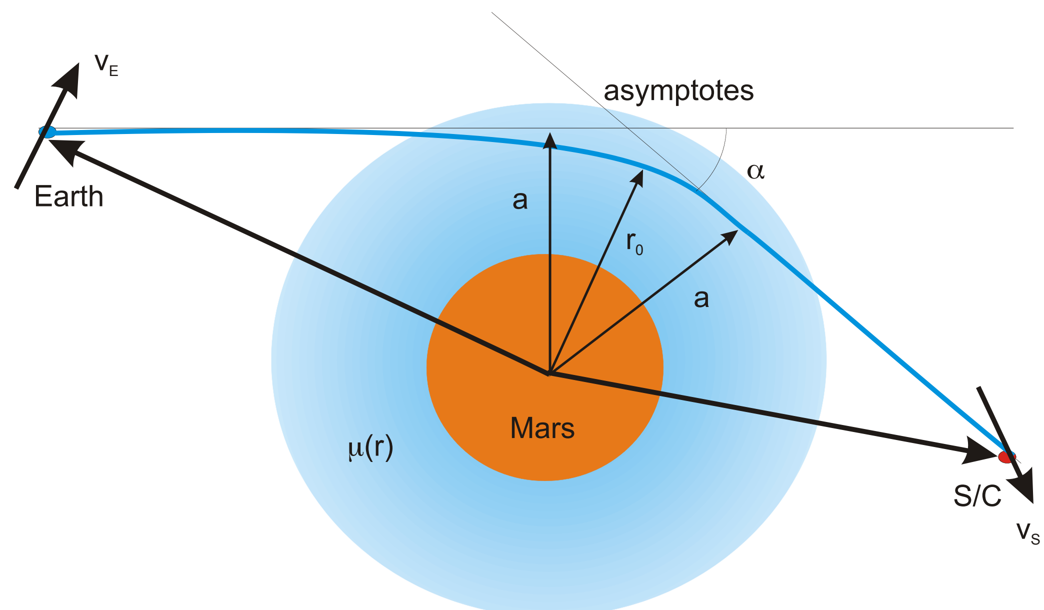
- It became apparent with early missions that occultations by planetary atmospheres would affect the quality of radio communications
- *One person's noise is another's data*
- Study the atmospheric properties
  - And other aspects of planetary science, solar science, and fundamental physics
- A recognized field of solar system exploration with instrument distributed between spacecraft & ground stations



Occultation by the atmosphere of the Sun

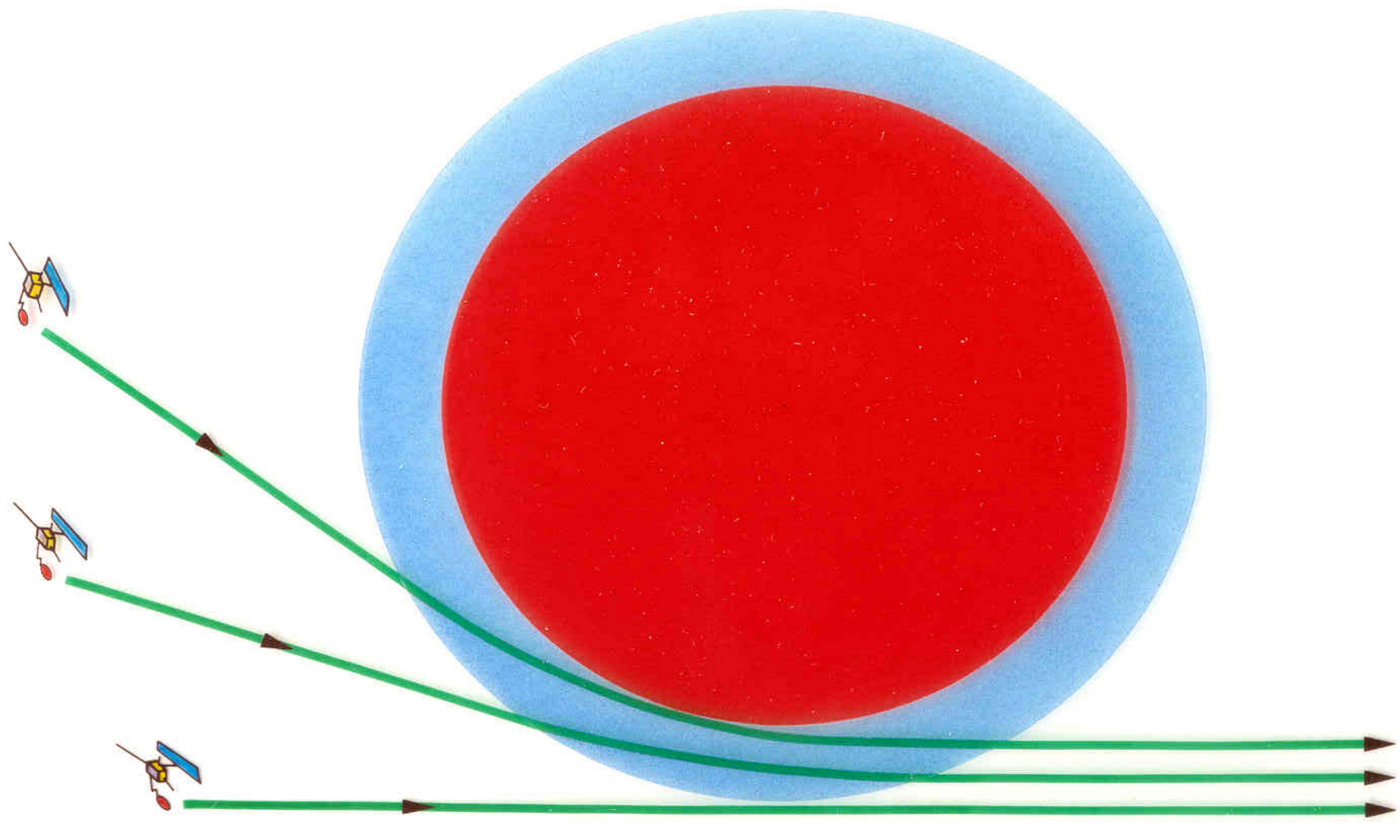


Occultation by the atmosphere of Mars



Radio Atmospheric Occultation Methodology

Phase ==> length ==> refractive angle ==> refractivity ==> number density ==>column pressure ==> temperature



Radio Atmospheric Occultation Formulations

Two frequencies are needed to separate dispersive (plasma) from non-dispersive effects (orbit, neutral atmosphere, systemic errors, …)

Refraction index of plasma

$$n = 1 - \frac{40.3\left(m^3 s^{-2}\right) N_e}{f^2}$$

Group/phase change

$$T_{gr/ph} = \int \frac{ds}{v_{gr/ph}} = \frac{s}{c} \pm \frac{40.3}{c\,f^2} \int_0^s N_e\, ds$$

Received phase

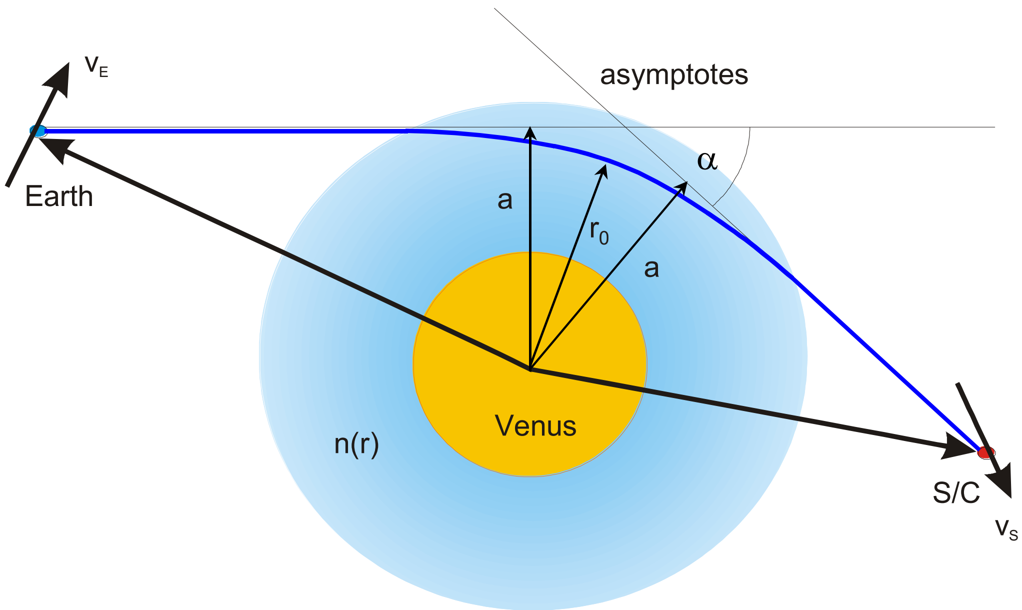
$$\theta_R(t) = 2\pi f_T \left[t - \frac{s(t)}{c} + \frac{40.3}{c\,f_T^2} I(t) \right]$$

Measured frequency at ground station

$$f_R(t) = \frac{1}{2\pi} \frac{d\,\theta_R}{dt} = f_T \left[1 - \frac{\dot{s}}{c} + \frac{40.3}{c\,f_T^2} \dot{I}(t) \right]$$

Straight Line Doppler Effect

Compare to effect without atmosphere to derive frequency Residuals



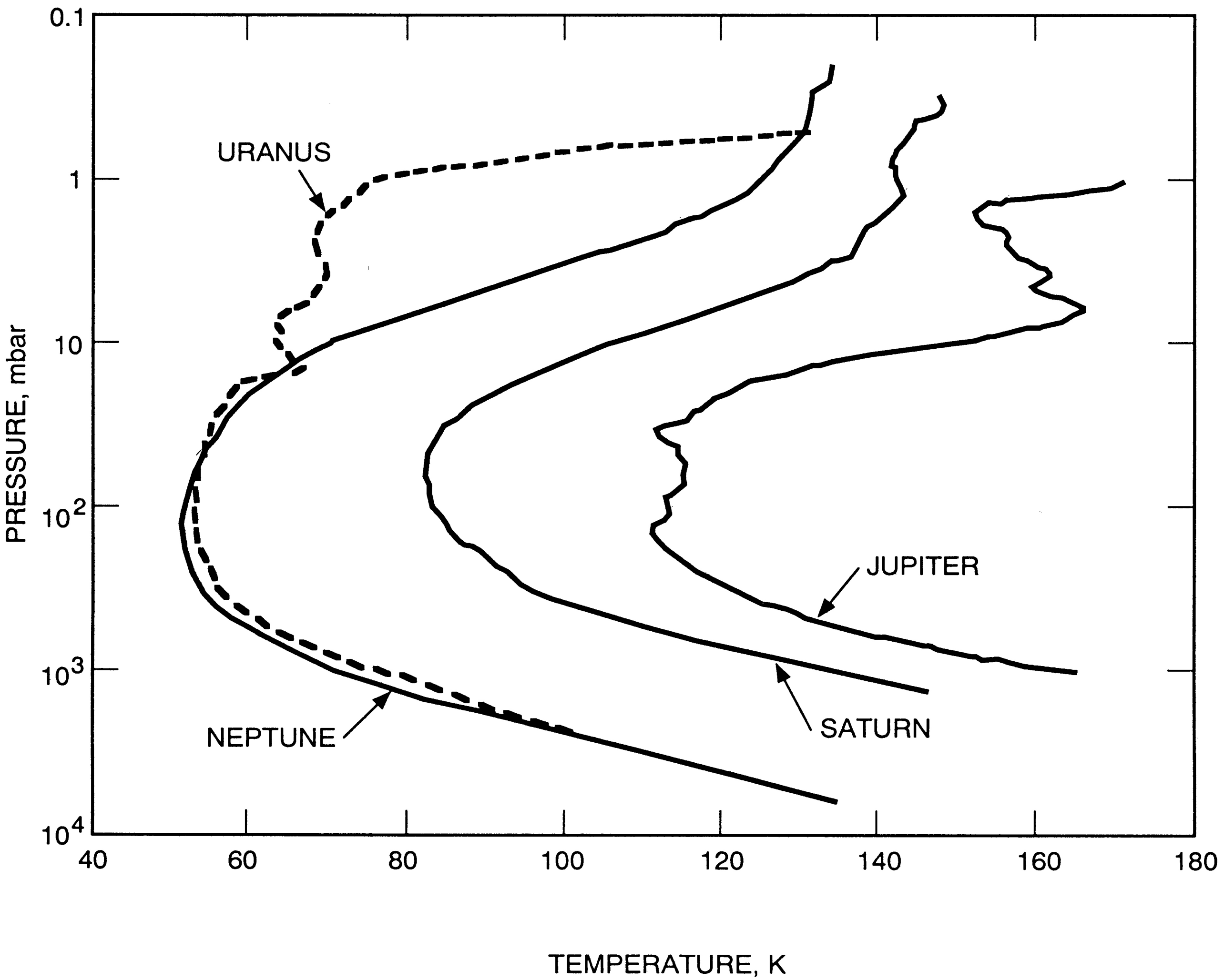
$$\phi = -\sum_i \frac{G \cdot M_i}{r_i}$$

$$\beta_{S,E} = \mathrm{v}_{S,E} / \mathrm{c}$$

$$\Delta f_0 = f_S - f_E = f_S \left\{ \hat{\mathbf{n}} \cdot \left(\boldsymbol{\beta}_E - \boldsymbol{\beta}_S \right) + \frac{1}{2}\left(\beta_S^2 - \beta_E^2 \right) + \left(\hat{\mathbf{n}} \cdot \boldsymbol{\beta}_S \right)\left(\hat{\mathbf{n}} \cdot \boldsymbol{\beta}_E \right) - \left(\hat{\mathbf{n}} \cdot \boldsymbol{\beta}_S \right)^2 - \frac{1}{c^2}\left(\varphi_S - \varphi_E \right) \right\}$$

Valid in an inertial (barycentric) system

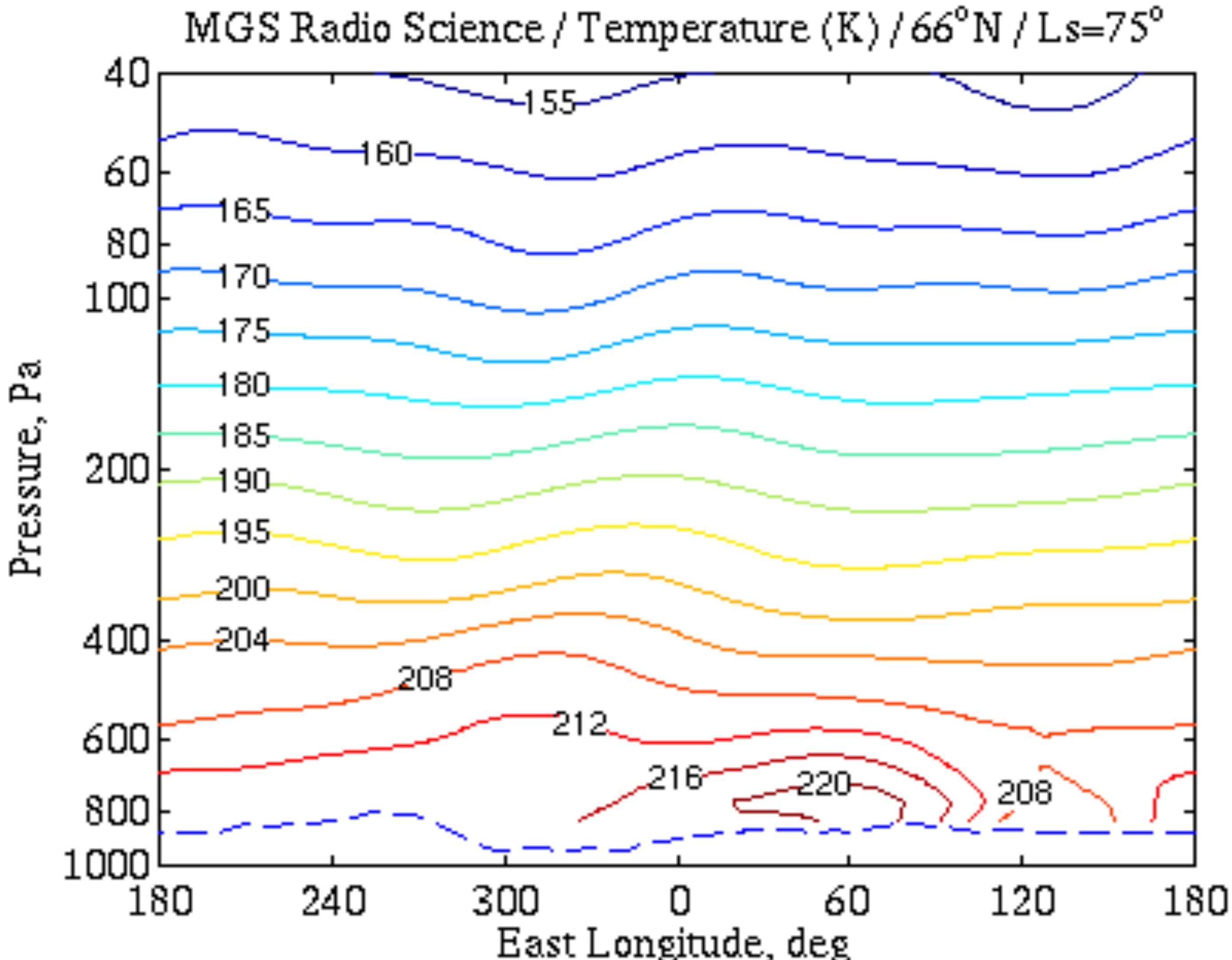
Atmospheres of Giant Planets



Temperature profiles for the giant planets derived from radio occultation data acquired with the Voyager spacecraft (from Lindal, 1992)

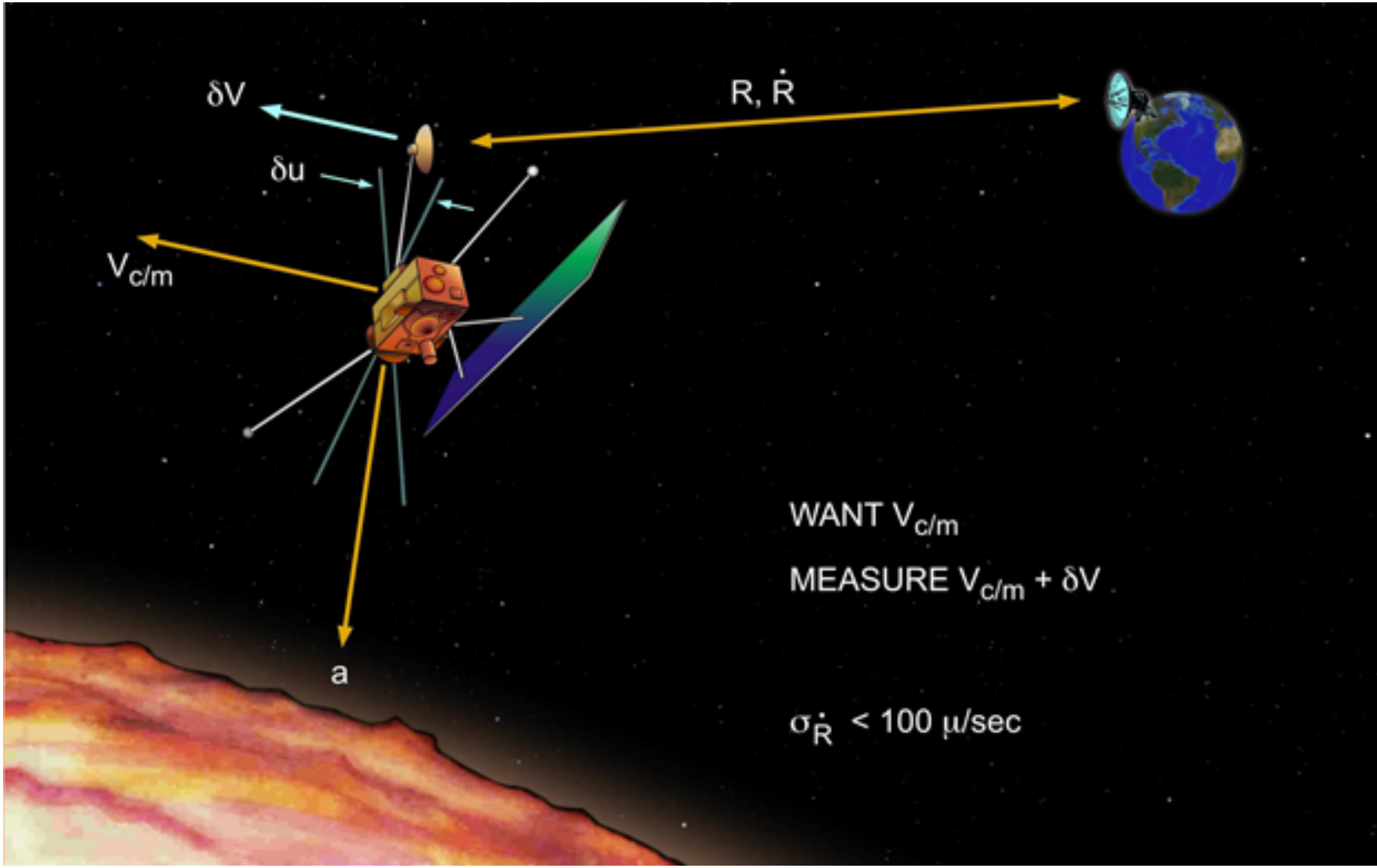
Occultations of Voyager 2 by outer planets

Atmosphere of Mars from MGS Occultations



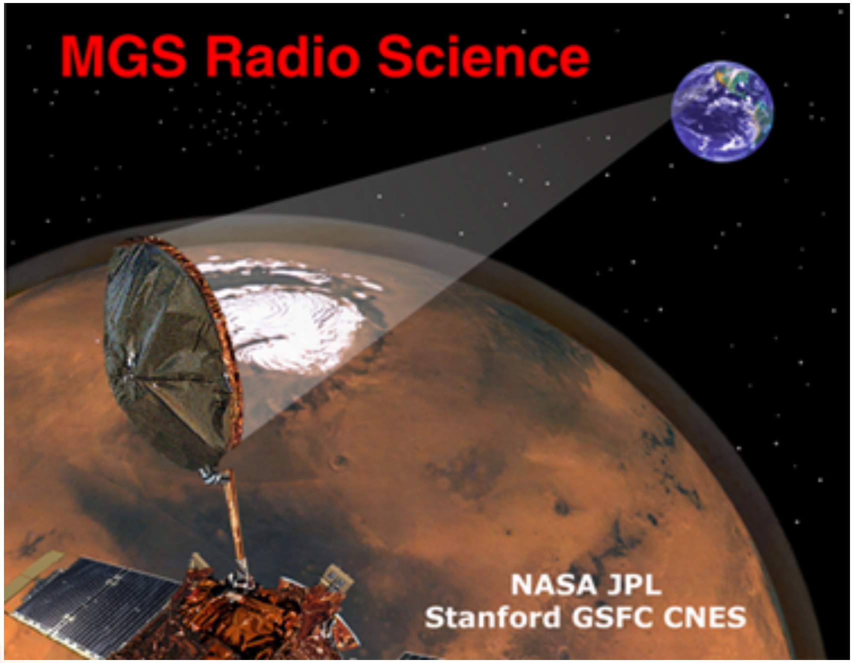
Source: D. Hinson

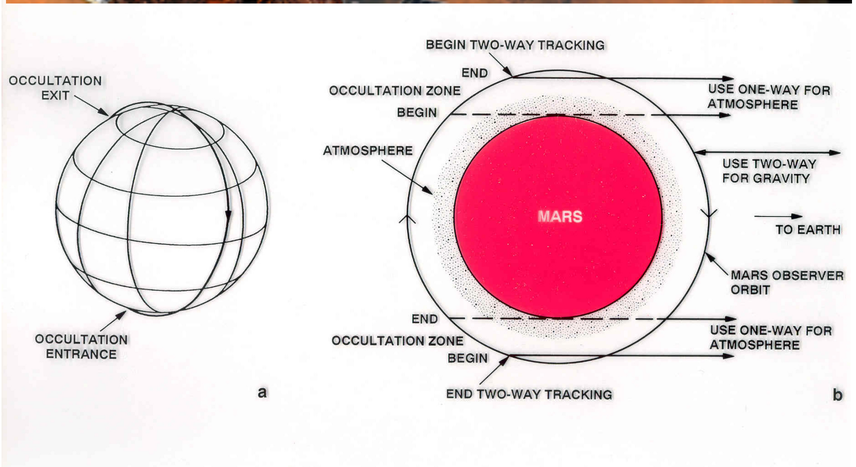
Doppler Observable



Radio Science Experiment Types

- Propagation
  - Study media
  - Remove effects of forces
- Gravitation
  - Study forces
  - Remove effects of media





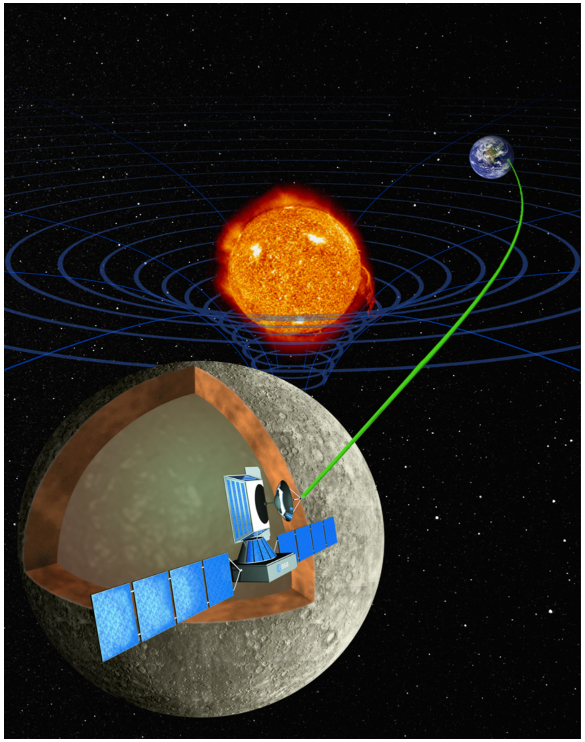
Time Share Example

Mars Global Surveyor Radio Science Team conducted both types of experiments back-to-back every orbit for thousands of orbits: *Propagation* to study the atmosphere and *Gravitation* to study the interior

Radio Science Investigations

Utilize the telecommunication links between spacecraft and Earth to examine changes in the phase/frequency, amplitude, and polarization of radio signals to investigate:

- **Planetary atmospheres**
- **Planetary rings**
- **Planetary surfaces**
- **Planetary interiors**
- **Solar corona and wind**
- **Comet mass flux**
- **Fundamental Physics**



Definitions

- Downlink bands (frequencies and wavelengths):
  - S-band: ~2.3 GHz ~13 cm
  - X-band: ~8.4 GHz ~3.6 cm
  - K_a-band: ~ 32 GHz ~1 cm
- Uplink frequencies derived via transponder ratio
- Relation between bands key to dispersive relations

Table 3. Channel frequency ratios

Band pair	Channel frequency ratio
2110-2120 MHz, 2290-2300 MHz	$\frac{221}{240}$
7145-7190 MHz, 8400-8450 MHz	$\frac{749}{880}$
2290-2300 MHz, 8400-8450 MHz	$\frac{3}{11}$

Table 1. Spacecraft Transponder Turnaround Ratios†

Uplink	Downlink	Ratio (downlink/uplink)
S	S	240/221
S	X	880/221
S	K_a	15.071 – 15.235*
X	S	240/749
X	X	880/749
X	K_a	4.4506 – 4.4923*
K_a	S	0.066959 – 0.066282*
K_a	X	0.24561 – 0.24352*
K_a	K_a	0.92982 – 0.93084*

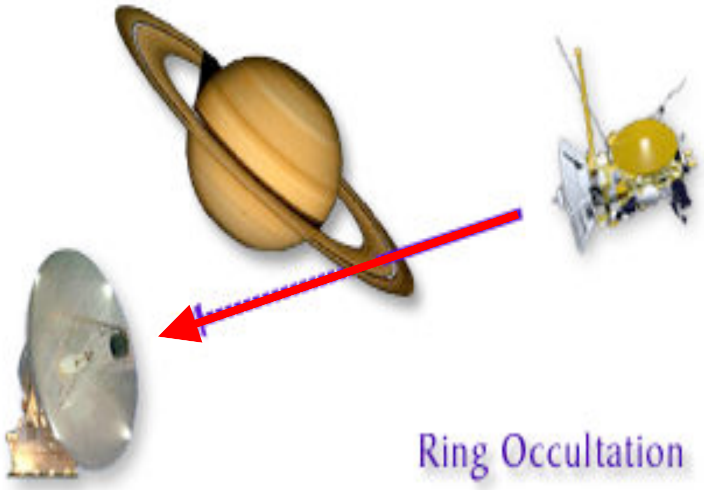
Signal Modes

- **Coherency Mode**
  - **One-way: signal referenced to source onboard spacecraft**
  - **Two-way: downlink coherent with uplink signal**
  - **Three-way: uplink and downlink at different stations**
  - **Four-way: Sometimes used for relay satellites**

- **Reception mode**
  - **Closed-loop: find, lock-on, and track received signal**
  - **Open-loop: down-convert and record in pre-selected bandwidth using a prediction of signal profile**

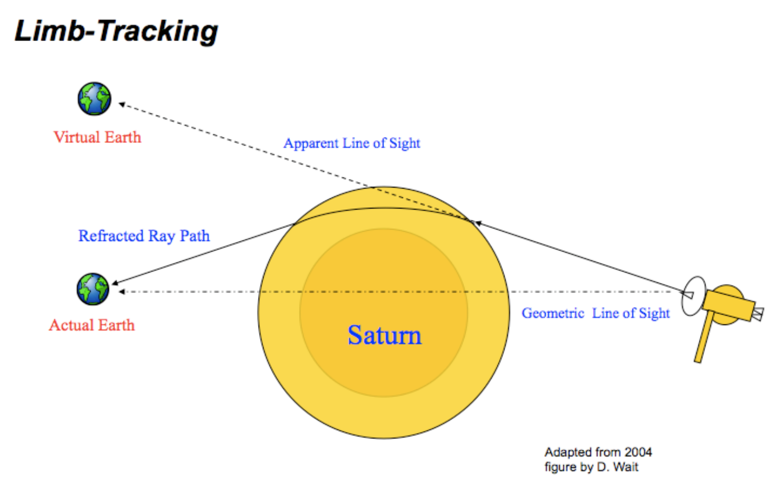
Radio Occultations

- Study properties of planetary media along propagation path
  - Atmosphere: temperature-pressure profile
  - Ionosphere: electron density
  - Rings: particle structure and size distribution
  - Byproducts: planetary shapes
- Observables:
  - Amplitude and phase
    - Refraction
    - Scattering
    - Edge diffraction
    - Multi-path

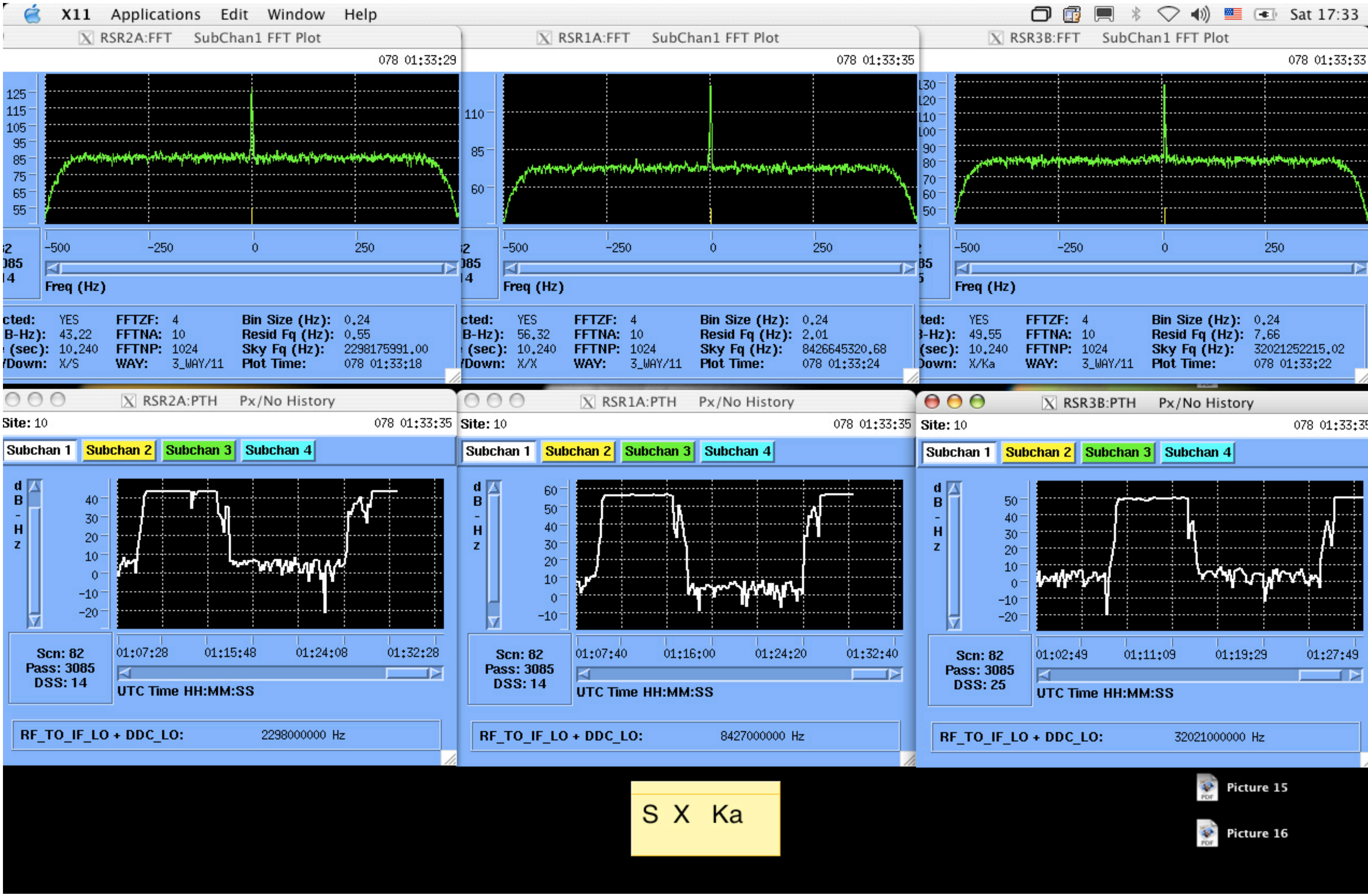


Occultation Experiment Requirements

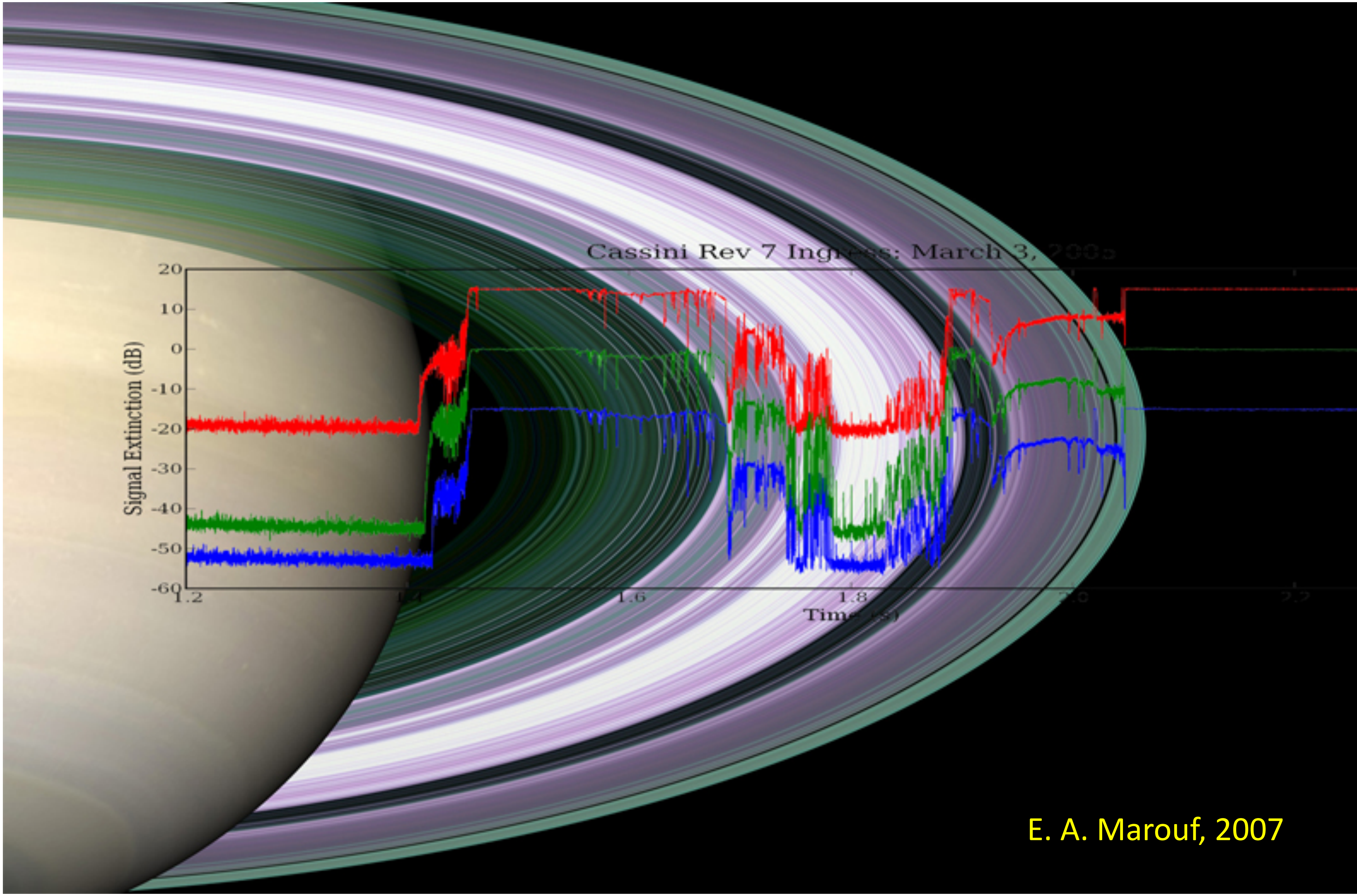
- **Stable pointing of spacecraft antenna to Earth**
  - **Possibly requires limb-tracking maneuver**
- **Optimum signal-to-noise ratio**
  - **Ideally turn off telemetry modulation**
- **One-way downlink referenced to an Ultra Stable Oscillator**
- **Open-loop Radio Science Receiver at Deep Space Network**
- **Optimized pointing of ground station**
  - **Possibly blind pointing**
  - **Sometimes fixing sub-reflector**
- **Avoid low station elevation angles**



Three Cassini Signals Occulted by Titan

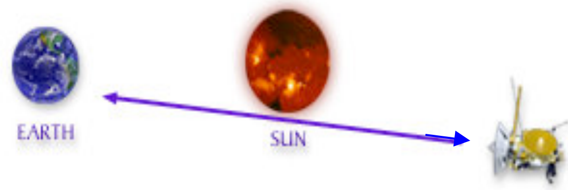


Saturn's Rings In the Cassini Era



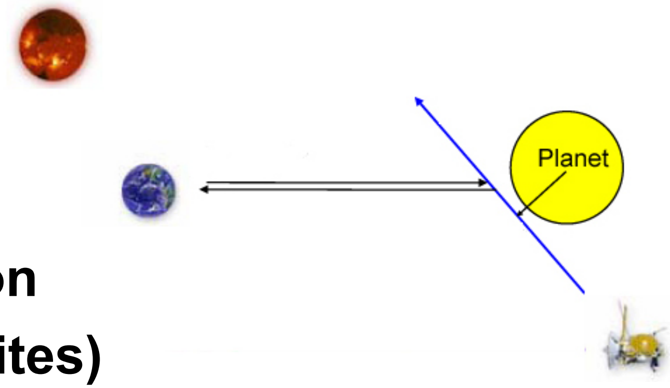
E. A. Marouf, 2007

Solar Corona and Solar Wind



- Occultation by Sun during conjunction periods
  - Derive electron density profiles
  - Deduce speeds of winds and coronal mass ejections
  - Investigate magnetic field via Faraday rotation
- Observables:
  - Frequency scattering: spectral broadening
  - Range: columnar-charged particles effect on group velocity
  - Doppler: fluctuations function of integrated electron density
- Configuration:
  - Two-way link for uplink carrier modulated with range code
  - Multiple downlink frequencies (dispersive medium)
  - Open-loop receiver supplementing tracking receiver

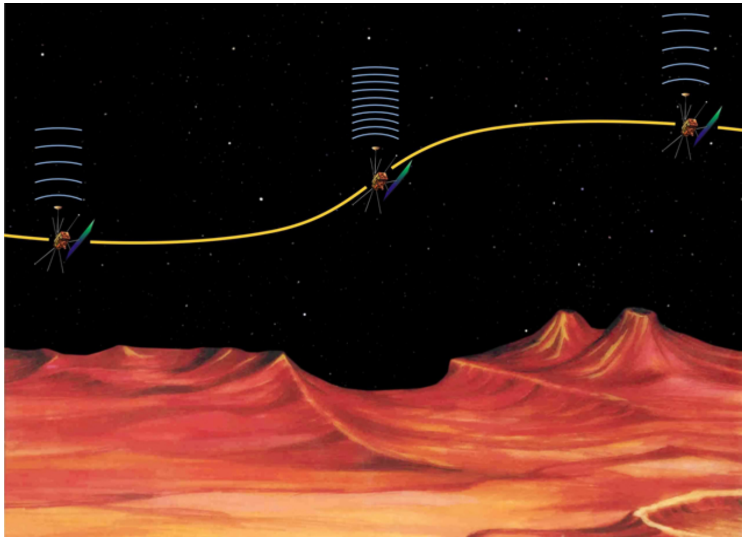
Gravity and Planetary Interiors



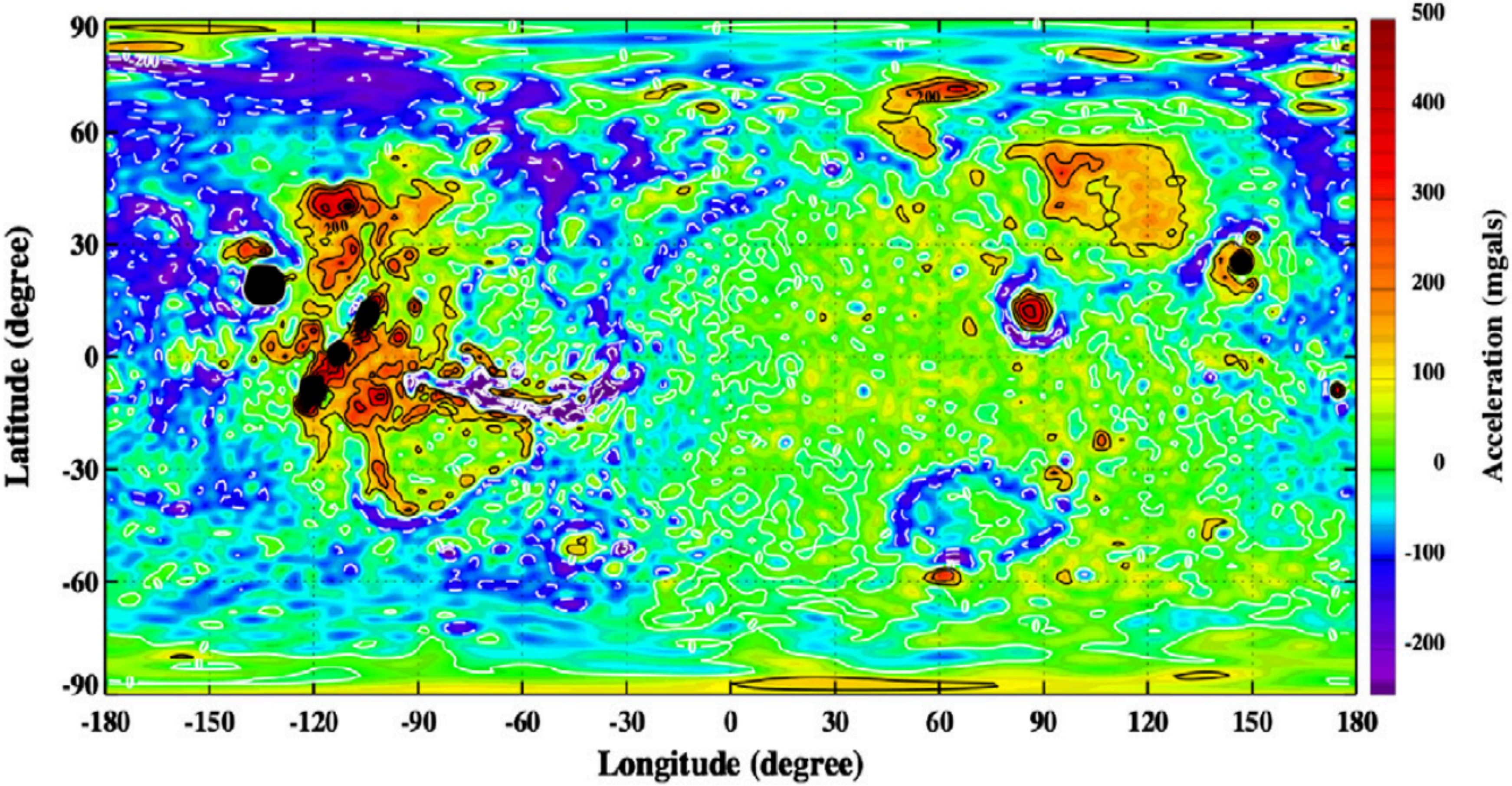
- Determine the mass and mass distribution
  - GM of body or system (planet + satellites)
  - Gravity field: higher order expansion of mass distribution
- Constrain models of internal structure
  - Examples: ocean on Europa
- Improve orbits and ephemerides
- Observables:
  - Doppler and range: precise measurement of relative motion
    - Doppler accuracy ~ 0.03 mm/s at X, few microns/s at Ka-band
    - Ranging accuracy to ~ 1 meter

Gravity Experiment Requirements

- Two-way links when possible
  - Superior stability of ground clocks
- Minimized non-gravitational accelerations
  - Reaction wheels versus thrusters
  - Antennas on a long boom
  - Fuel sloshing
- Tracking receiver: Doppler and ranging
  - Open-loop receiver fill in data gaps when high signal dynamics
- Higher frequencies and dual links to reduce noise



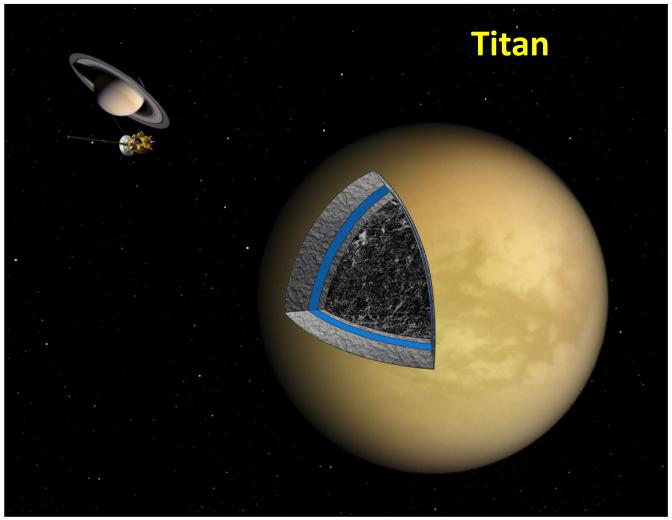
The Gravity Field of Mars



Surface gravity anomalies complete to degree and order 90 with respect to a reference ellipsoid (model MRO110B)

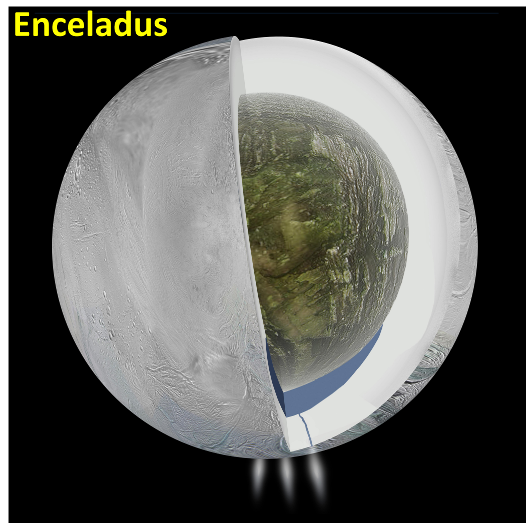
Konopliv et al., 2011

Moons of Large Planets

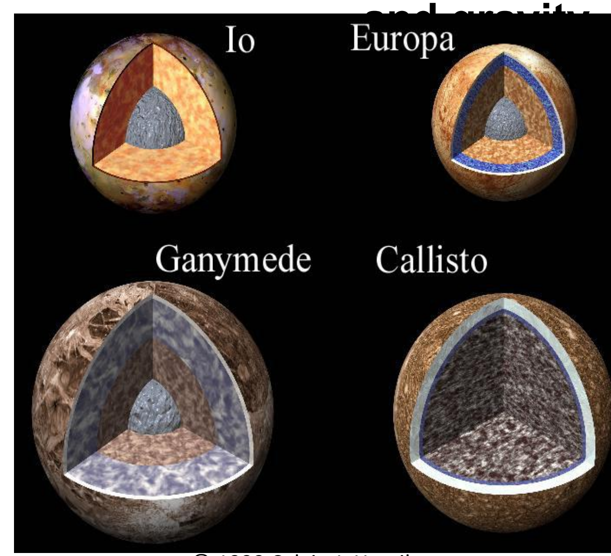


Tidal observations by Cassini gravity team

Titan: Iess et al., 2011 & 2012
Enceladus: Iess et al., 2014



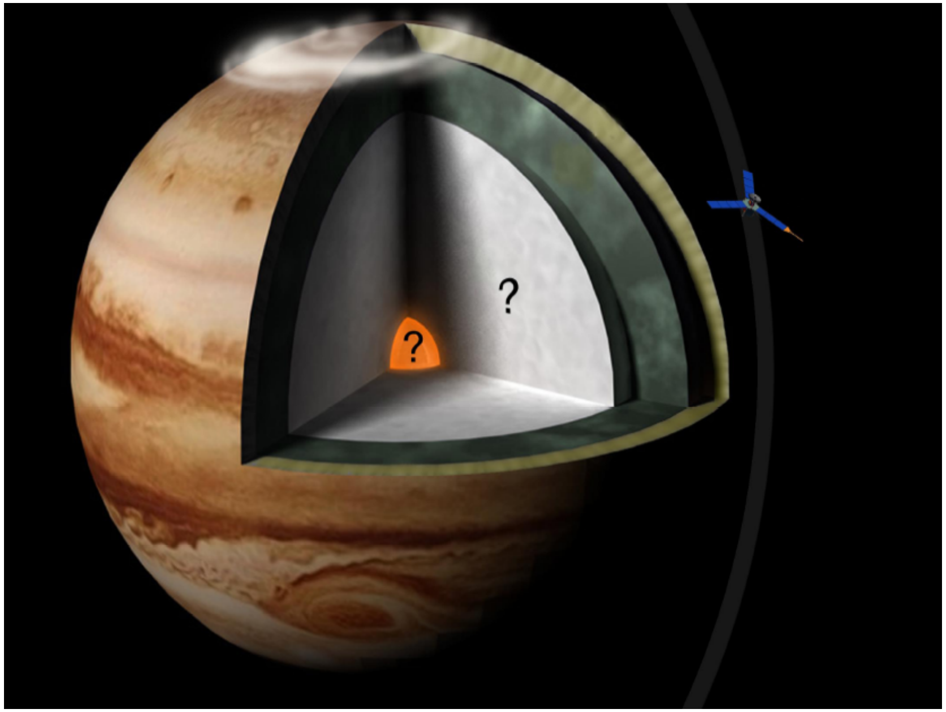
Models of the interiors of the Galilean satellites based on magnetic



Juno To Reveal Jupiter 's Interior Structure

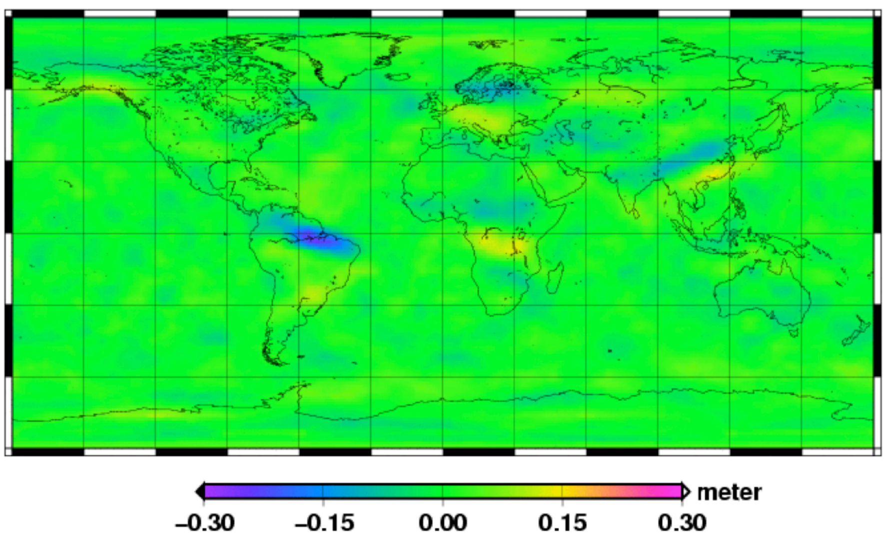
Juno Gravity Science:

- **Precise measurement of spacecraft motion measures gravity field**
- **Close-in Juno polar orbit maximizes sensitivity to gravity**
- **Distribution of mass reveals core and deep structure**
- **Higher degree harmonics reveal convective motion in deep atmosphere**

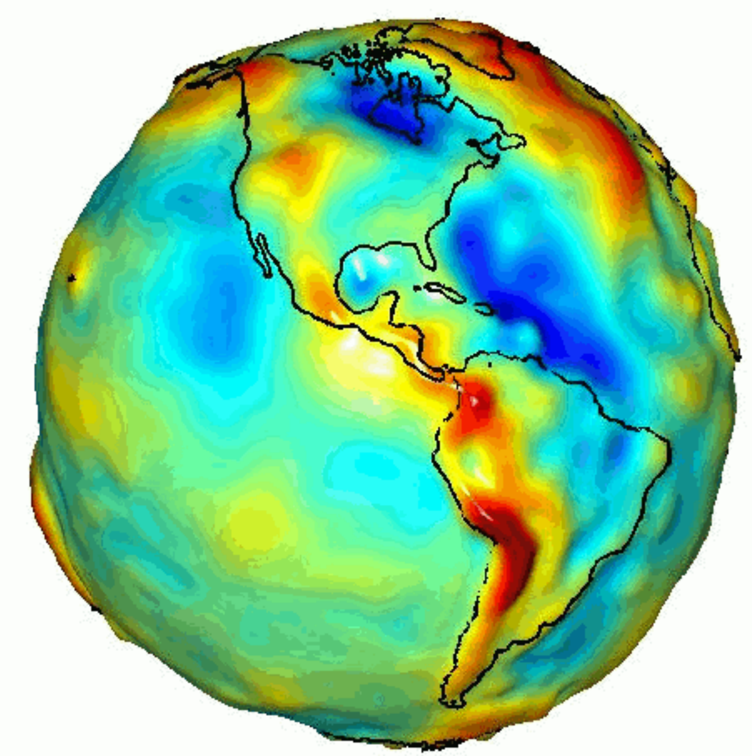


Earth's Gravity Varies with Time

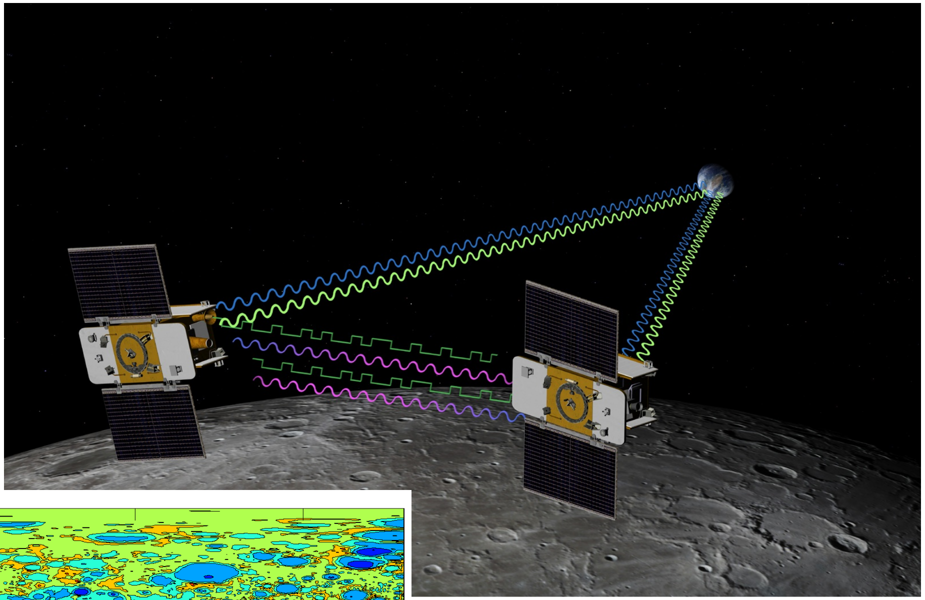
- Earth's gravity varies due to mountains and valleys as well as different density in the materials beneath the surface
- Bumpiness changes monthly due to water movement

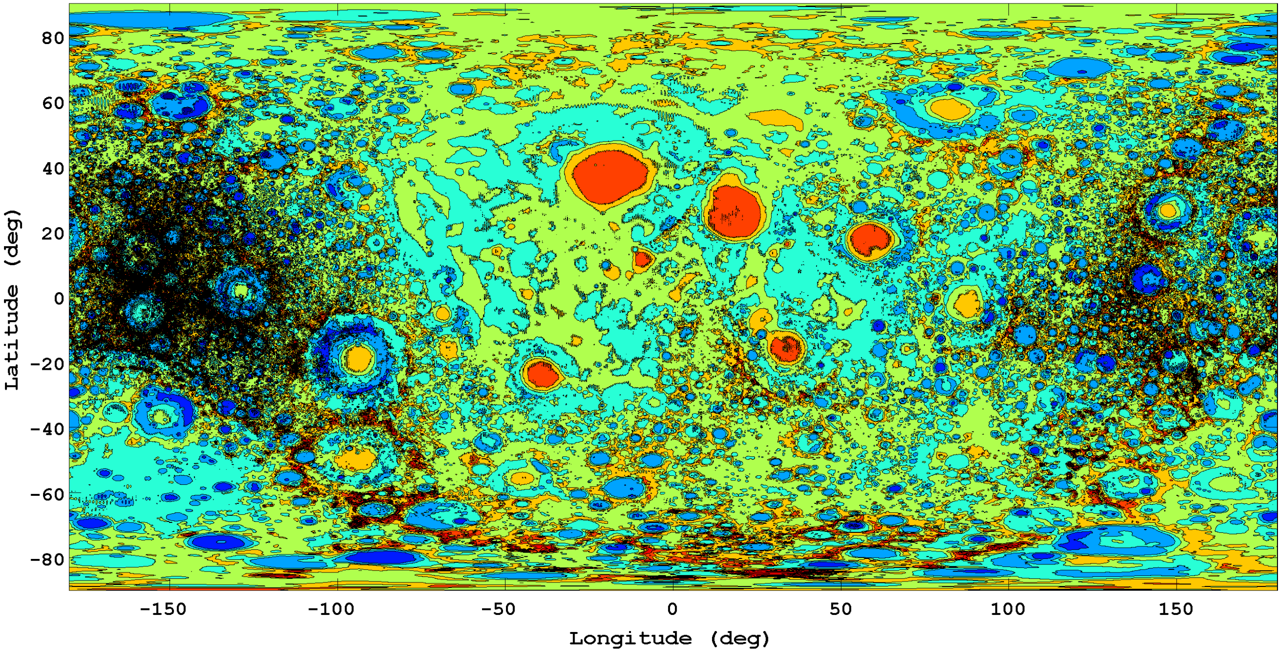


- Monthly surface mass variation in equivalent water height - annual wet & dry seasons
- Strongest signal over Amazon basin



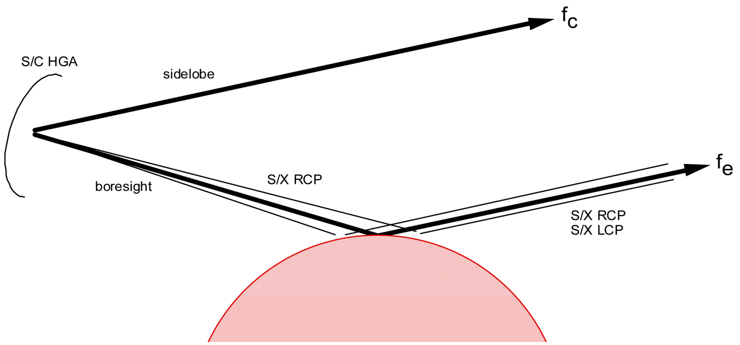
GRAIL Reveals Lunar Interior Structure

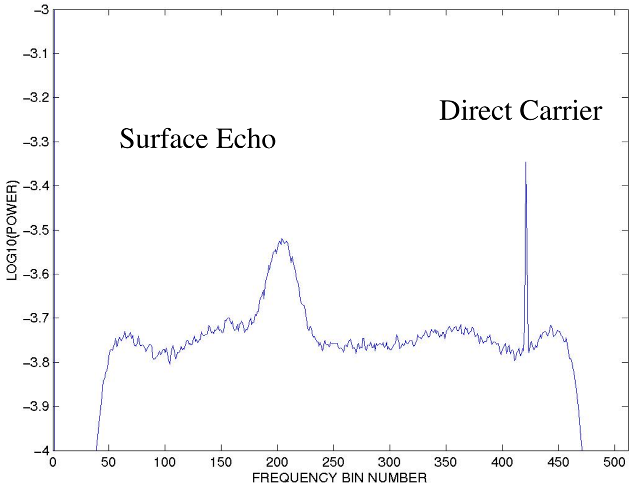




Surface Characteristics

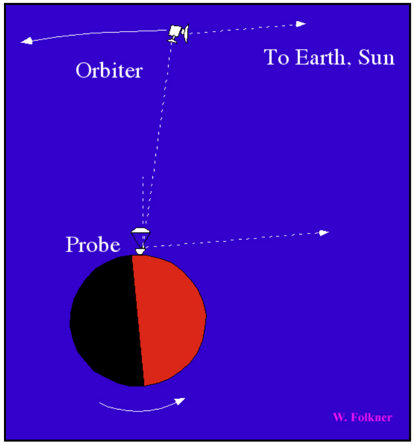
- Study properties of planetary surfaces
  - Roughness & dielectric constant
- Observables:
  - Ratio of received energy in same and opposite polarizations
- Configuration:
  - Point to planet's surface and receive echo on Earth
  - Record both polarizations
  - Special noise calibration procedures
  - Open-loop receivers
  - One-way downlink



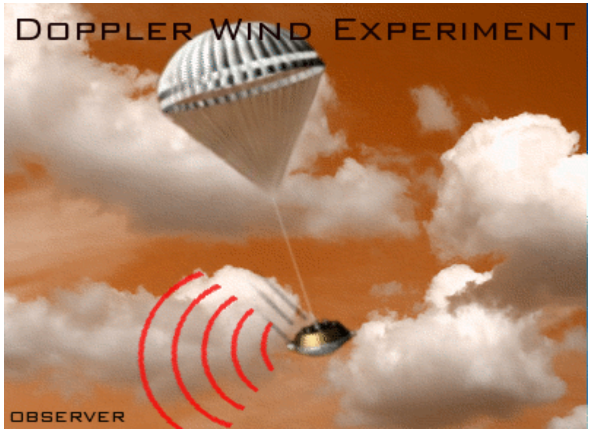


Source: R.A. Simpson & M. Patzold

Doppler Wind Experiments



- Deduce wind speed and direction as probe descends into atmosphere of planet or satellite
  - Huygens Probe at Titan
  - Galileo Probe into Jupiter
  - Russian probes at Venus
- Configuration:
  - Stable oscillators on probe and orbiter
  - Spacecraft-to-spacecraft links
  - Sometimes receive signal on Earth
- Huygens DWE failed but saved by recording at Green Bank and Parkes radio telescopes
  - Prograde zonal winds above boundary layer
  - Low-velocity layer between 60-80 km
  - Considerable turbulence above 100 km



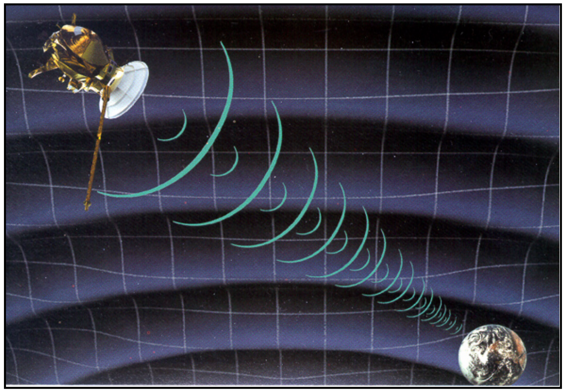
Relativistic Time Delay

- Determine Post-Newtonian Parameters
  - Bending due to Sun's gravitational potential
  - Formulated in General Theory of Relativity
  - Parameter describes curvature of space-time
- Observe time delay from frequency shift
- Cassini Solar Conjunction experiment in 2002
  - Gamma = $1+(2.1 \pm 2.3)\times 10^{-5}$
- Multiple links to calibrate interplanetary plasma
- Water vapor radiometer to calibrate troposphere
- Precise antenna pointing
- Open-loop and tracking receivers
- Quiet Spacecraft: reaction wheels

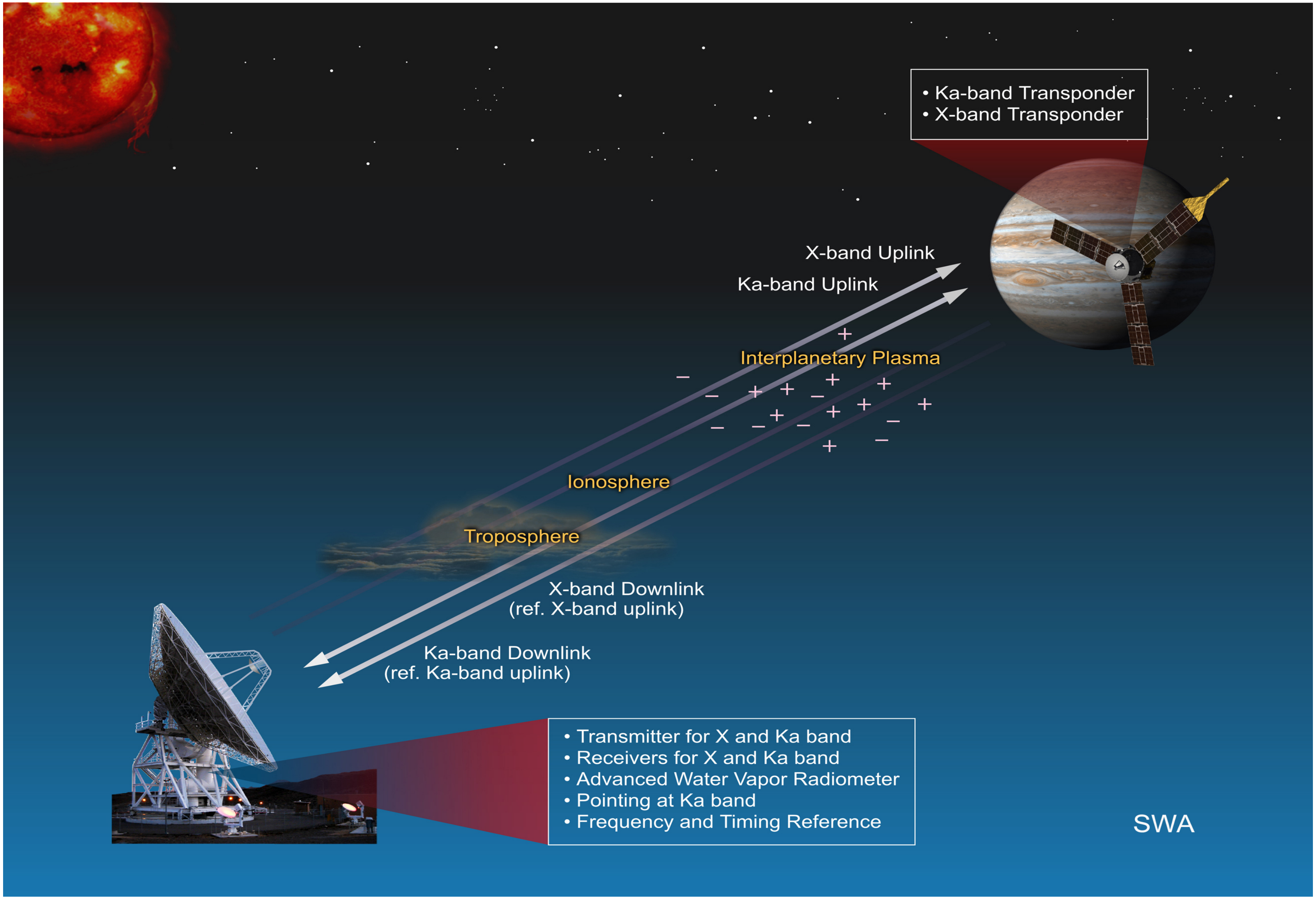
Bertotti et al. 2003

Search for Gravitational Waves

- Search for gravitational waves crossing the solar system
  - Propagating, polarized gravitational field
    - Predicted by all relativistic theories of gravity
    - Changes distance between separated test masses
    - Extremely weak; only detectable from astrophysical sources
  - Low frequency waves
    - Doppler method sensitive in milli-hertz range
- Observables:
  - Relative distance between spacecraft and ground station
    - Typically 40 days and 40 nights during solar oppositions



Largest Instrument in Solar System



Would not be able to do it without DSN

Composite image to show relative size of 70-meter diameter station

Cassini Meets Marconi

Uplink Possibilities

X-band ~ 7.9 GHz

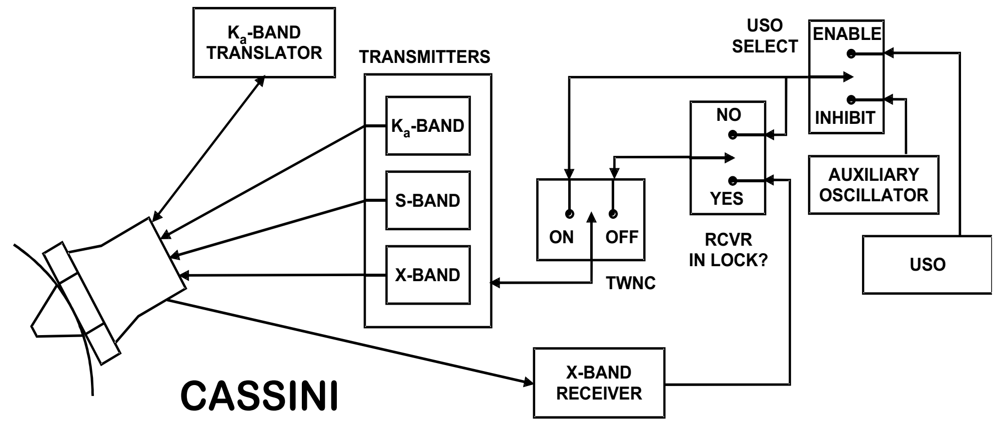
K_a-band ~ 34 GHz

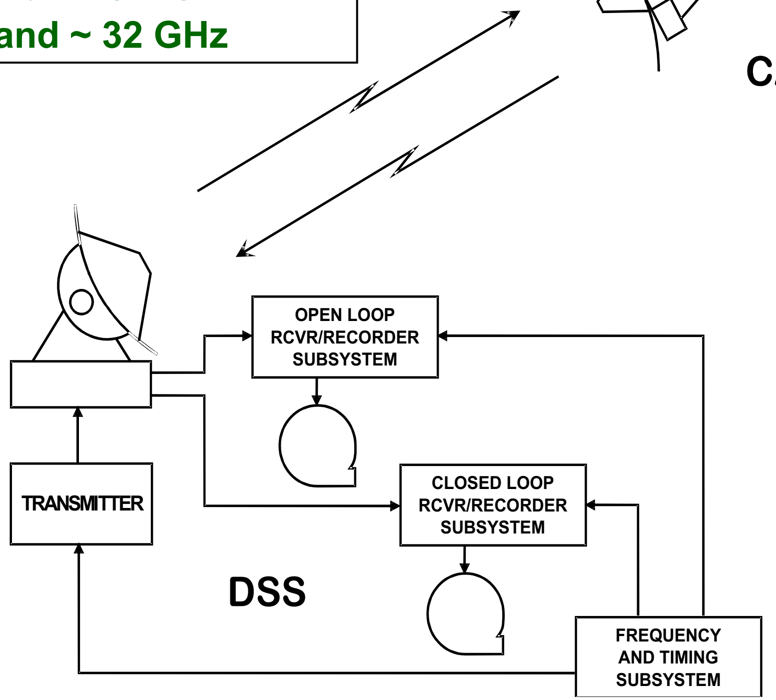
Downlink Possibilities

S-band ~ 2.3 GHz

X-band ~ 8.4 GHz

K_a-band ~ 32 GHz





HGA Gain ~ 47 dBi

Power ~ 20 W

EIRP ~ 88.6 dBm

Digital communication: BPSK

Bit rates: 5 bps to 248 kbps

Phase modulated onto carrier
or subcarriers of 360 or 22.5 kHz

Reed-Solomon outer code
Convolutional inner code